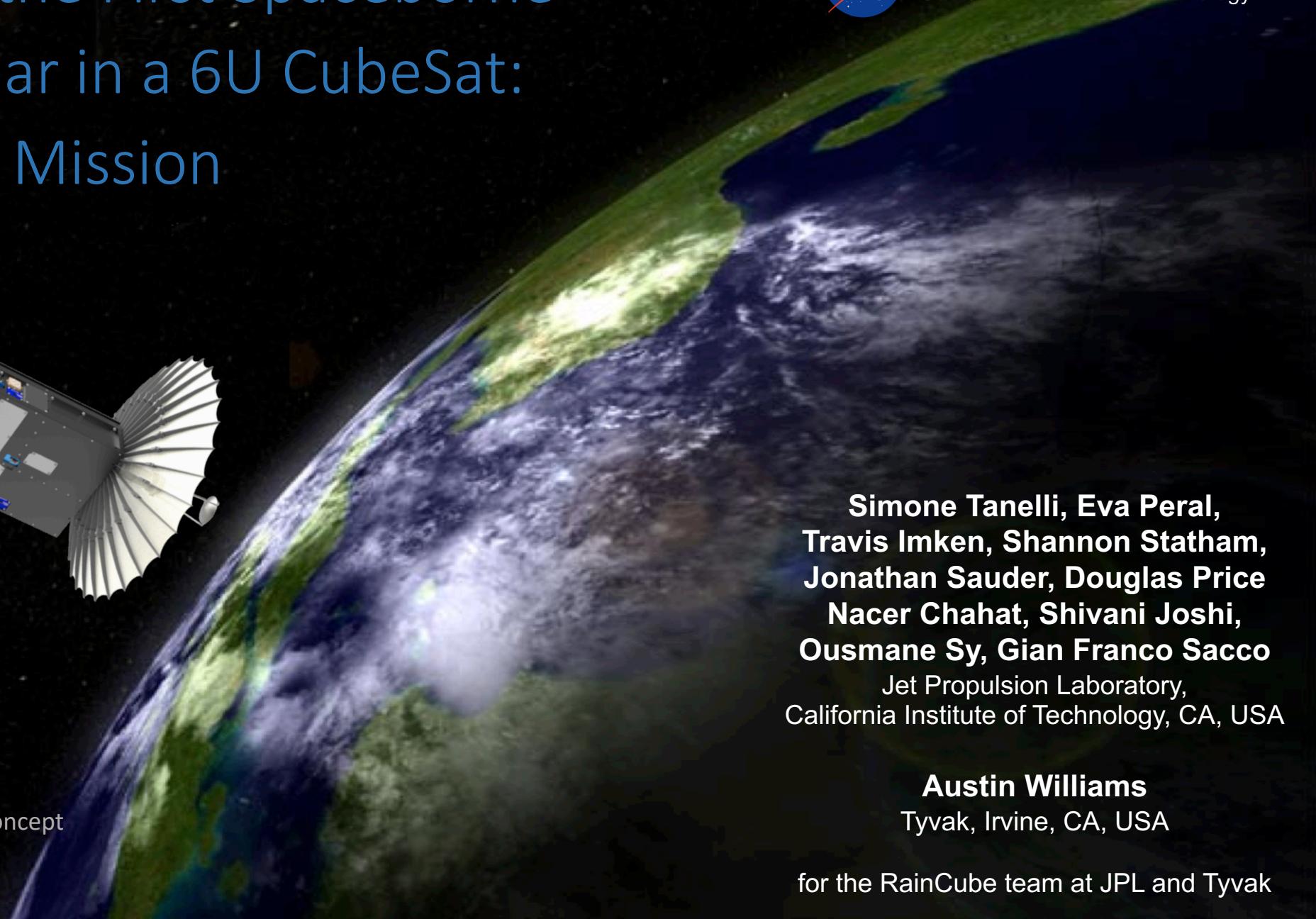
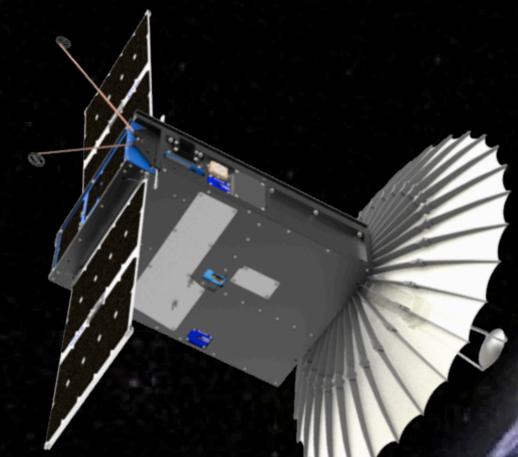




RainCube the First Spaceborne Precipitation Radar in a 6U CubeSat: From Concept to Mission



Jet Propulsion Laboratory
California Institute of Technology



**Simone Tanelli, Eva Peral,
Travis Imken, Shannon Statham,
Jonathan Sauder, Douglas Price
Nacer Chahat, Shivani Joshi,
Ousmane Sy, Gian Franco Sacco**

Jet Propulsion Laboratory,
California Institute of Technology, CA, USA

Austin Williams

Tyvak, Irvine, CA, USA

for the RainCube team at JPL and Tyvak

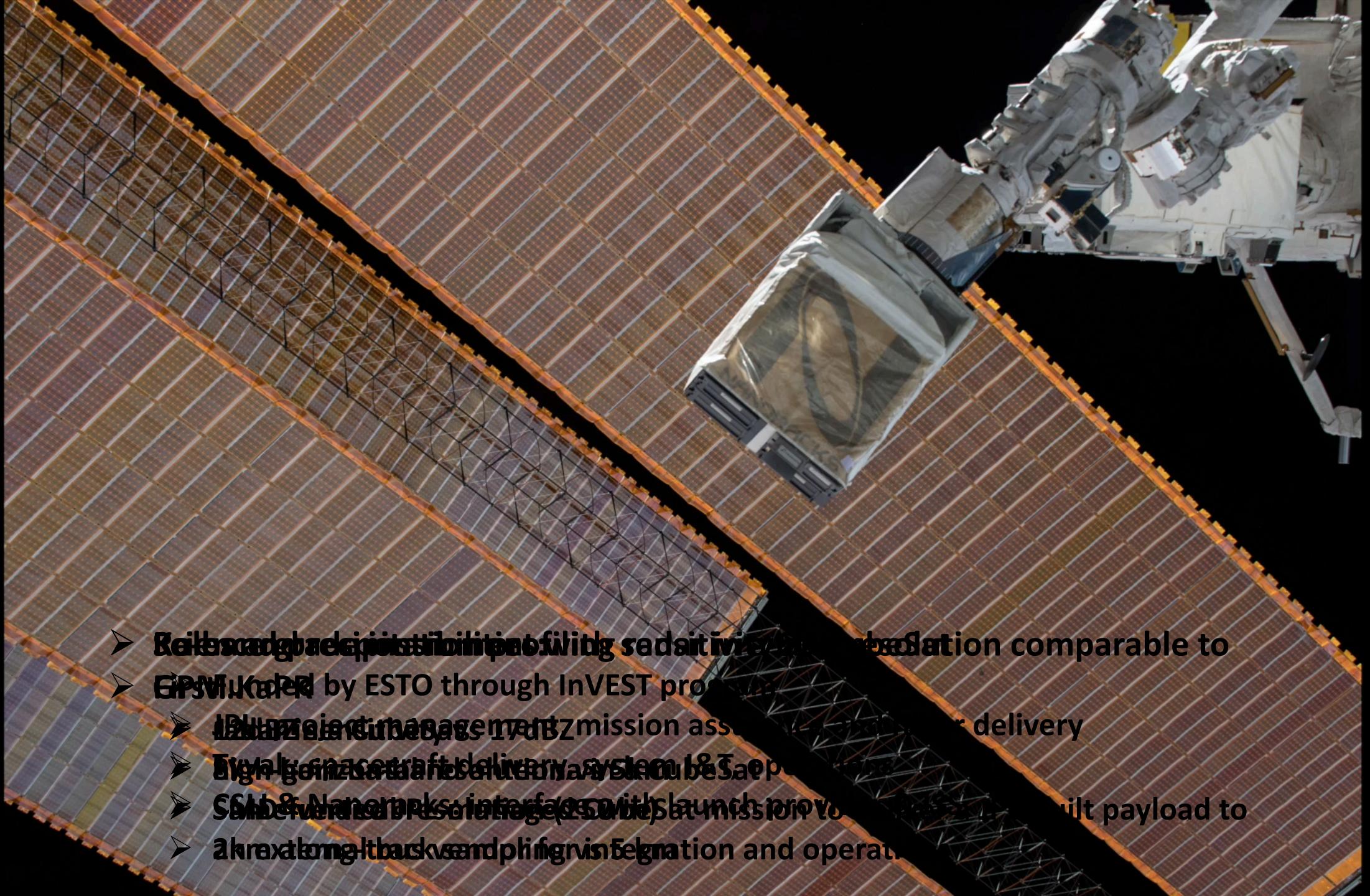


RainCube

Eva	Peral
Simone	Tanelli
John	Abel
Mario	Abesamis
Alessandra	Babuscia
Taryn	Bailey
Arlene	Baiza
Greg	Cardell
Steve	Carlson
Nacer	Chahat
Jan	Chaloeyphochana
Dominic	Chi
Marvin	Cruz
Brian	Custodero
Robert	Demerjian
Gregg	Dobrowalski
Steve	Durden
Chris	Ferguson
William	Fiechter
Stuart	Gibson
Ziad	Haddad
Jeff	Harrell
Rodolfo	Herrera
Richard	Hodges
Svetla	Hristova-Veleva
Travis	Imken
Shivani	Joshi

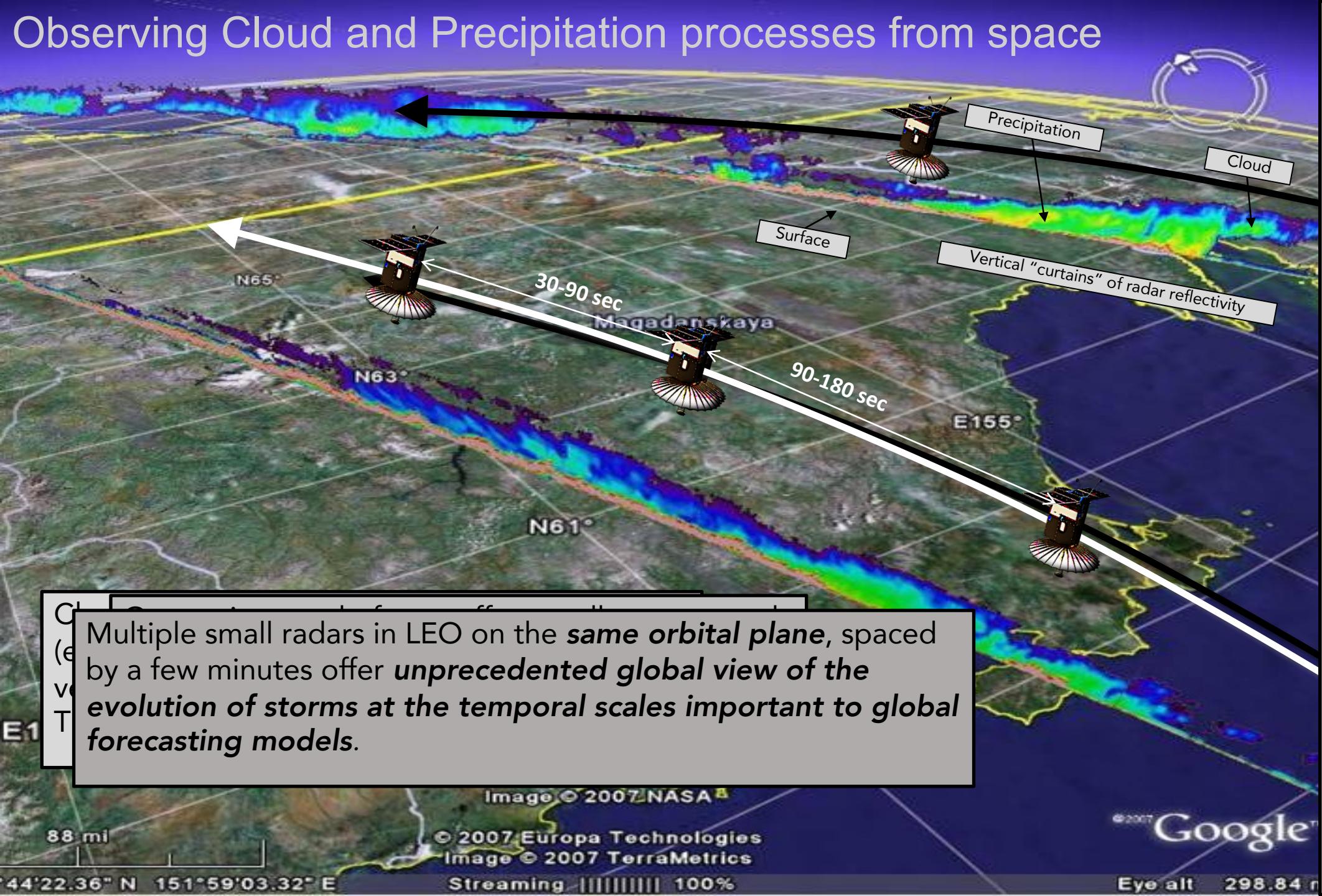
Jon	Kanis
Brian	Knosp
Marc	Lane
Kevin	Lo
Natalie	Lockwood-Barajas
Ninoslav	Majurec
Steve	Marroquin
Elvis	Merida
Jen	Miller
Pedro	Moreira
Sonny	Orellana
Brad	Ortloff
Chaitali	Parashare
Doug	Price
David	Pukala
Miguel	Ramsey
Richard	Rebele
Hugo	Rodriguez
Nazilla	Rouse
Gian Franco	Sacco
Jonathan	Sauder
Chris	Shaffer
Colin	Smith
Ryan	Sorensen
Mary	Soria
Shannon	Statham

Ousmane	Sy
Mike	Tran
Francis Joe	Turk
Marco	Villa
Kari	Kawashima
Stephen	Sundin
Craig	Francis
Curtis	Ridenour
Thomas	Entzion
Jeff	Weaver
John	Brown
John	Wagstaff
Lance	Collier
Ricky	Prasad
Sean	Fitzsimmons
Shin	Yamamoto
Jason	Price
Macon	Vining
Brandon	Wang
Duo	Wang
Austin	Williams
Joseph	Zitkus



- Re-imaging backplane technology for flight sat in orbit with resolution comparable to
- EPSV1.0 developed by ESTO through InVEST program
 - Utilizing management mission assistance for delivery
 - Evolved space craft delivery system & Safer
 - SAE 8 Nanometers interface with launch provider to built payload to
 - Averaging 10 bars wind proofing in Segmentation and operation

Observing Cloud and Precipitation processes from space



Clouds & Precipitation
(e.g., convective systems)

Multiple small radars in LEO on the **same orbital plane**, spaced by a few minutes offer **unprecedented global view of the evolution of storms at the temporal scales important to global forecasting models.**

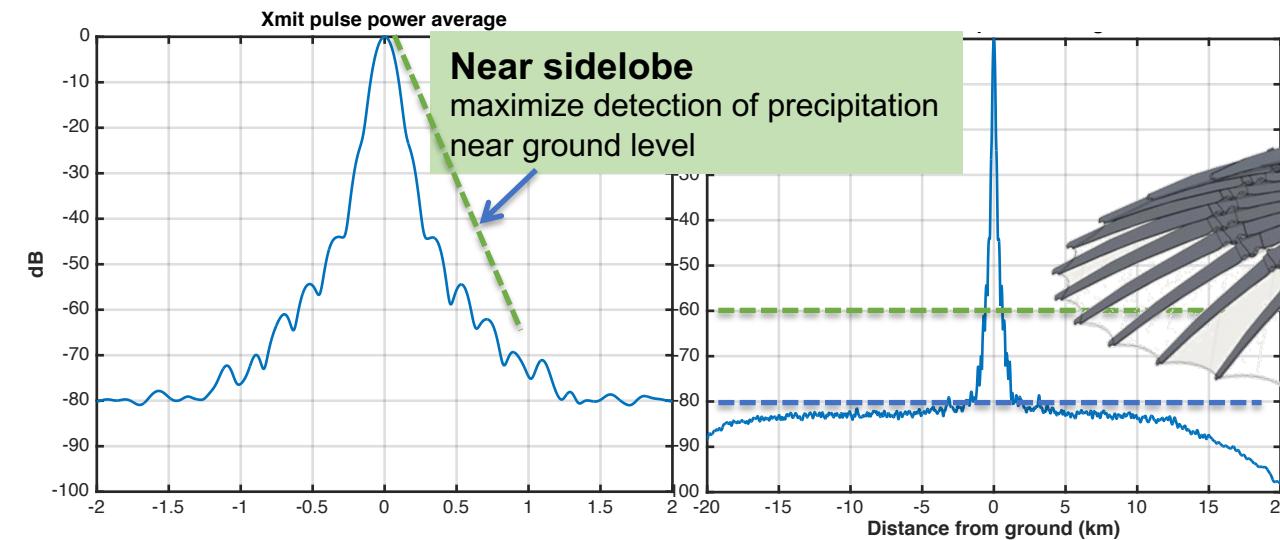
Inquiries for the feasibility of multiple cloud & precipitation radars in LEO were formulated during the development of TRMM and CloudSat (late 90's and early 00's).

Instrument and bus unit costs, and launch costs, didn't enable a realistic path to even propose such mission architectures... until the CubeSat (Nano, Micro, Small, ...) revolution.

First challenge was posed with 1U and 3U (no-go). Then the 6U became an option...

Radar Electronics & Antenna Reqs. (4U)

Req't Name	Requirement	Measured
Sensitivity @400km	20dBZ	11.0dBZ
Horizontal resolution @400km	10km	7.9 km
Nadir Data Window	0-18 km	-3 to 20 km
Vertical resolution	250m	250m
Downlink data rate (in transmit)	50 kbps	49.57 kbps
Payload power consumption (AntDeployment/STDBY/RXOnly/TXScience)	10 / 8 / 15 / 35 W	5 / 3 / 10 / 22 W
Mass	6 kg	5.5 kg
Range sidelobe suppression	>60dB @ 5km	>65dB @ 1km
Transmit power & Transmit loss	10W / 1.1dB	>39dBm
Antenna gain	42 dB	42.6 dB
Antenna beamwidth	1.2 deg	1.13 deg



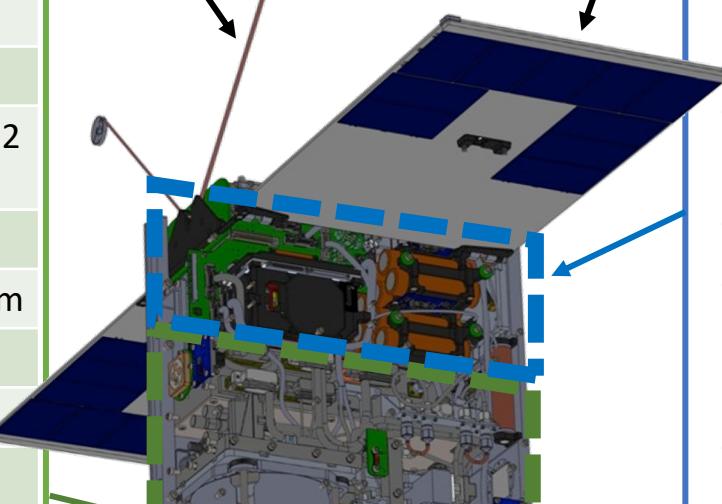
System Architecture

Deployable UHF Antenna

Deployable Solar Arrays

Bus Reqs. (2U)

- Provide 35 W for payload power in transmit mode
- Maintain a 25% radar duty cycle
- 12.1 Gb/week of payload data
- Maintain payload temperatures (-5C to +50C operational)
- GPS provides on-board altitude to radar

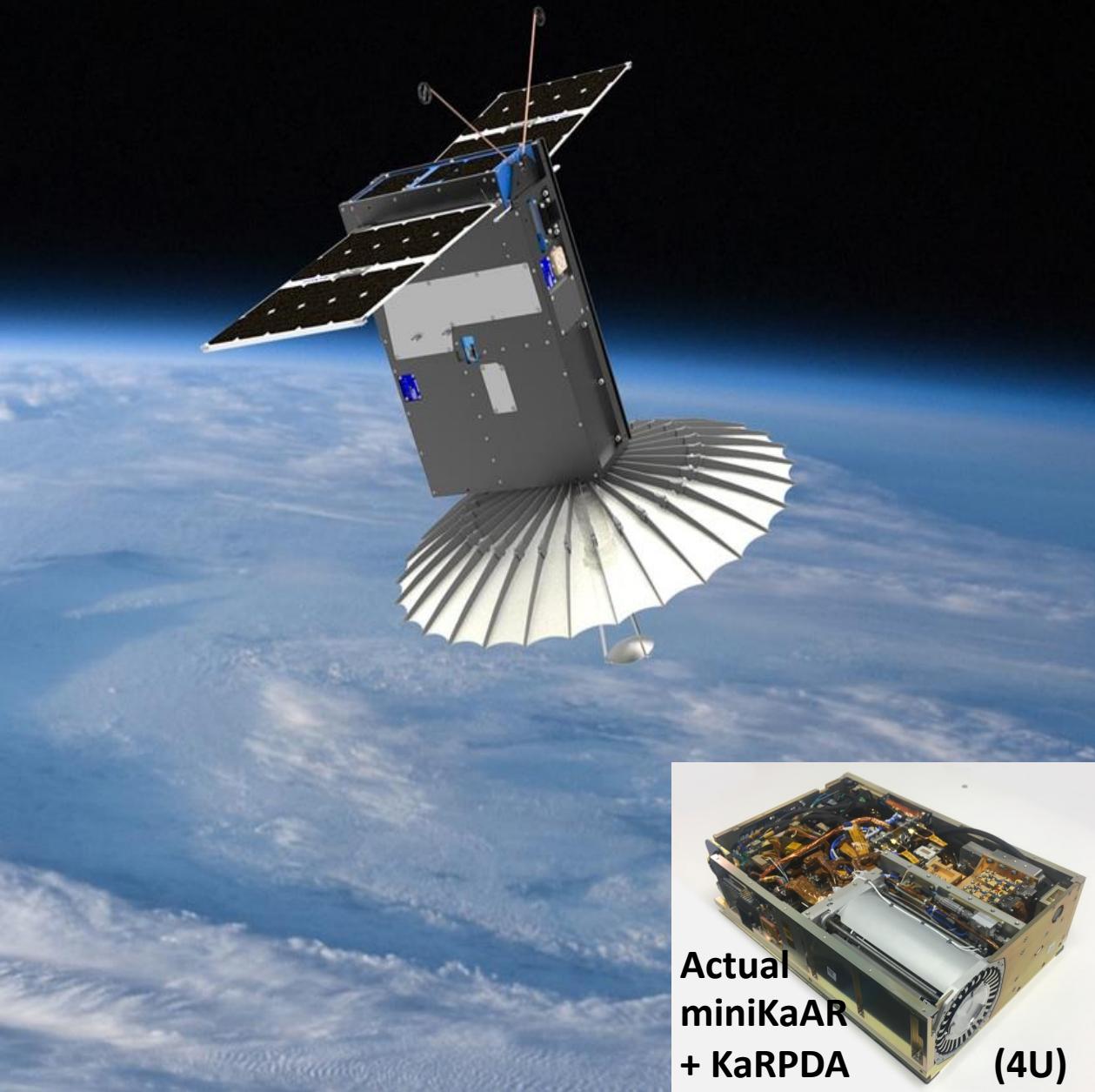


S-Band Patch Antenna &
Transmitter

Deployable
0.5 m KaRPDA
Radar Antenna

Far sidelobes below -60dB for clutter-free detection
in all conditions throughout the troposphere

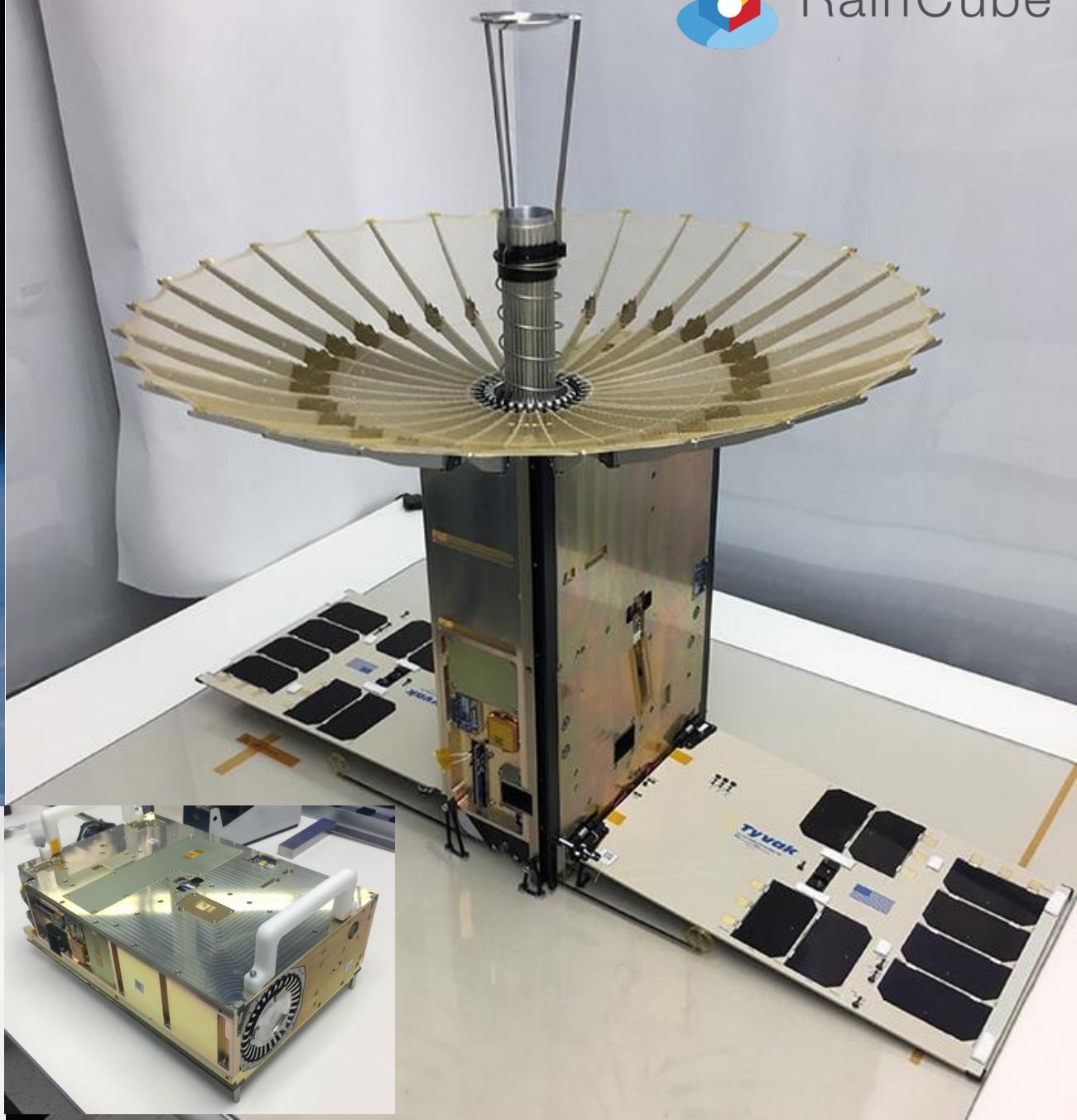
Radar in a Cubesat Concept



RainCube Flight Model



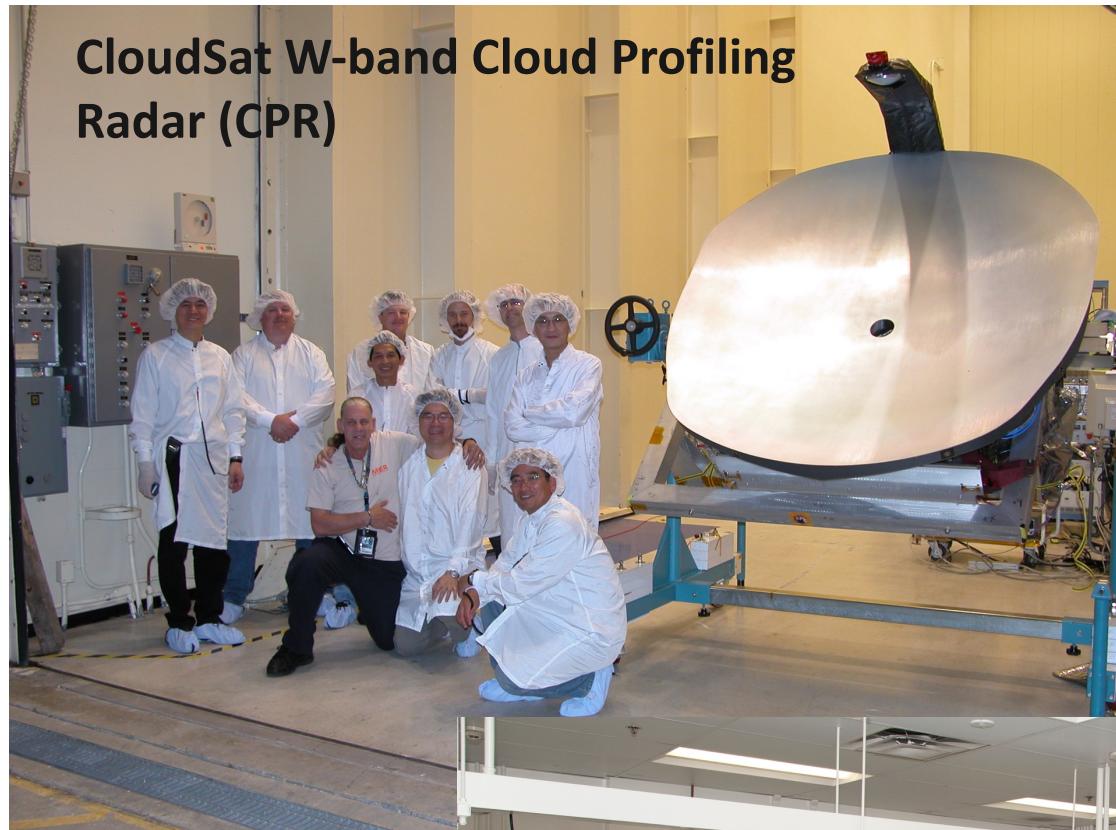
RainCube



Actual
miniKaAR
+ KaRPDA
(4U)



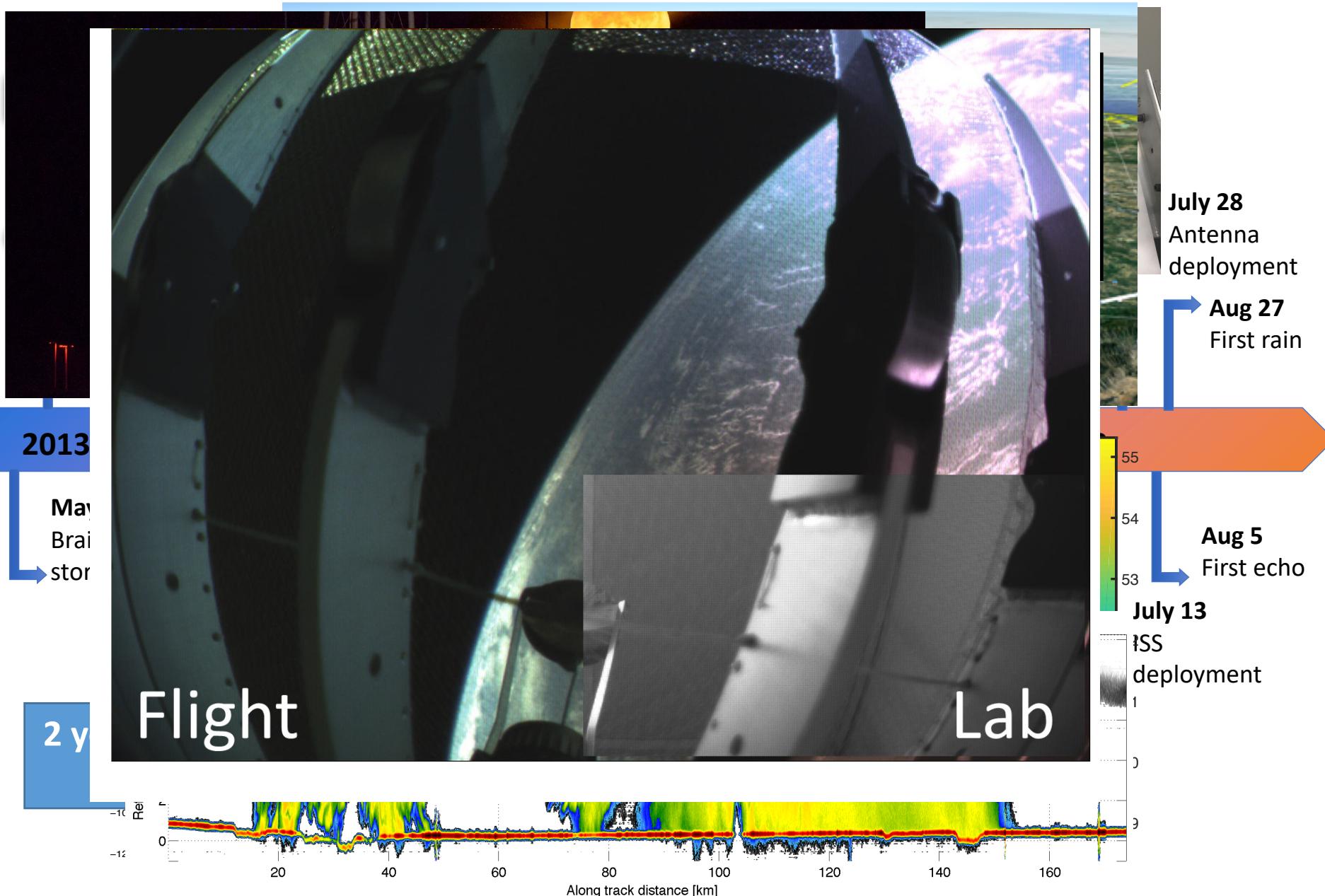
How small is RainCube. . .



	CPR	KaPR	RainCube
Mass [Kg]	260	336	7
Power [W]	300	344	22
Volume [U]	4,356	1,210	4
Class	C	C	Tech demo
Frequency	W-band	Ka-band	Ka-band
Scanning	No	Yes	No
Sensitivity	-30 dBZ	+17 dBZ	+12 dBZ

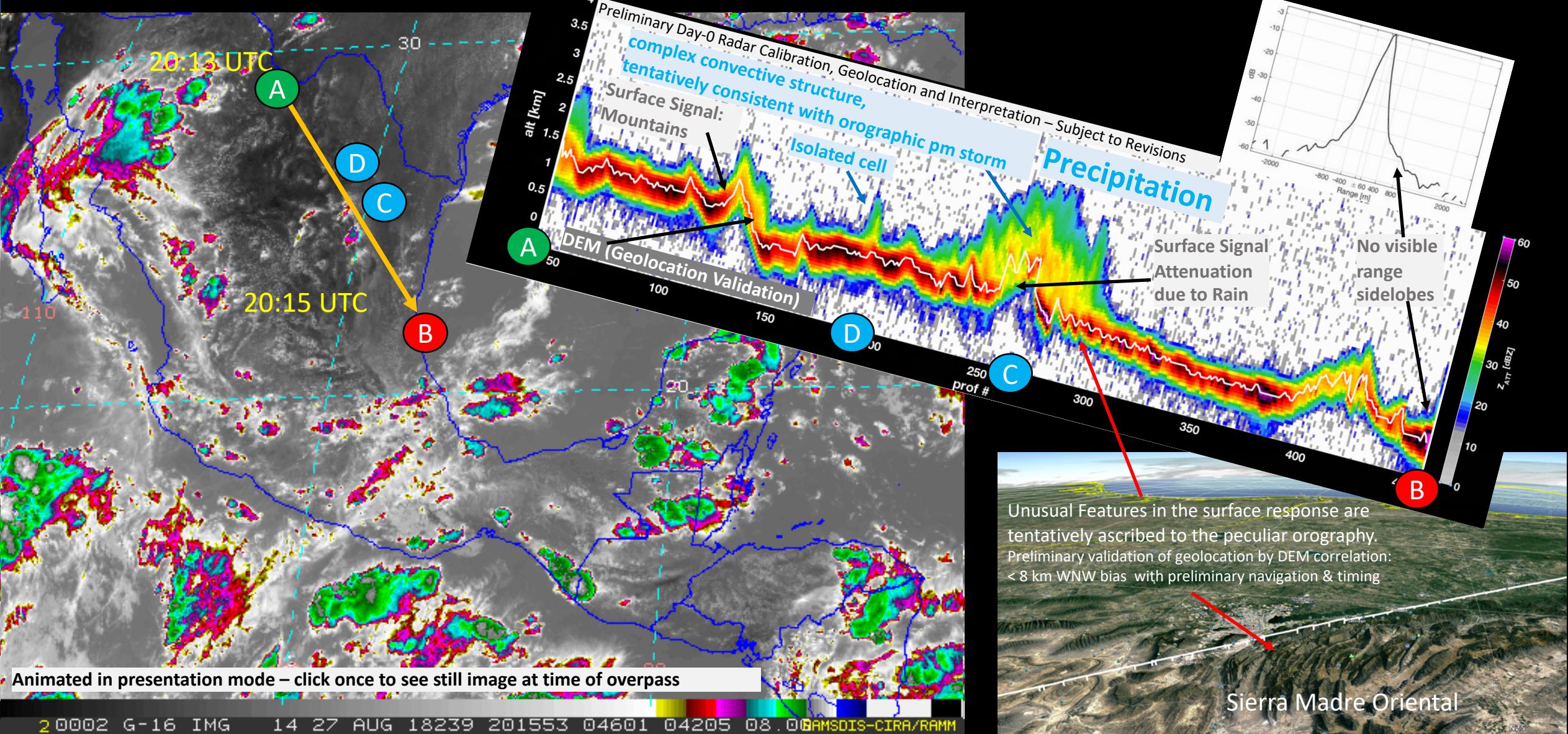


Timeline from TRL 0 to TRL 7

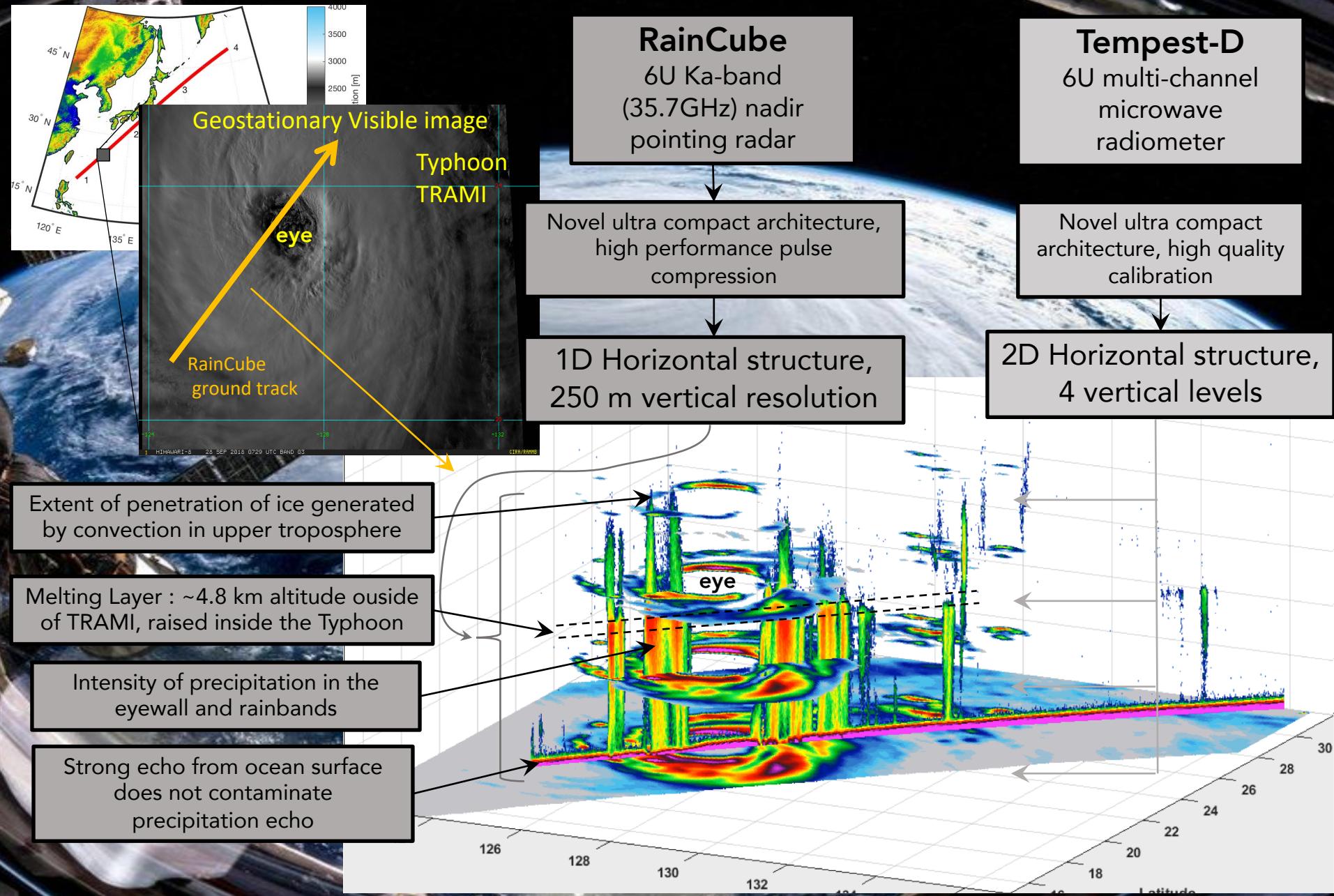




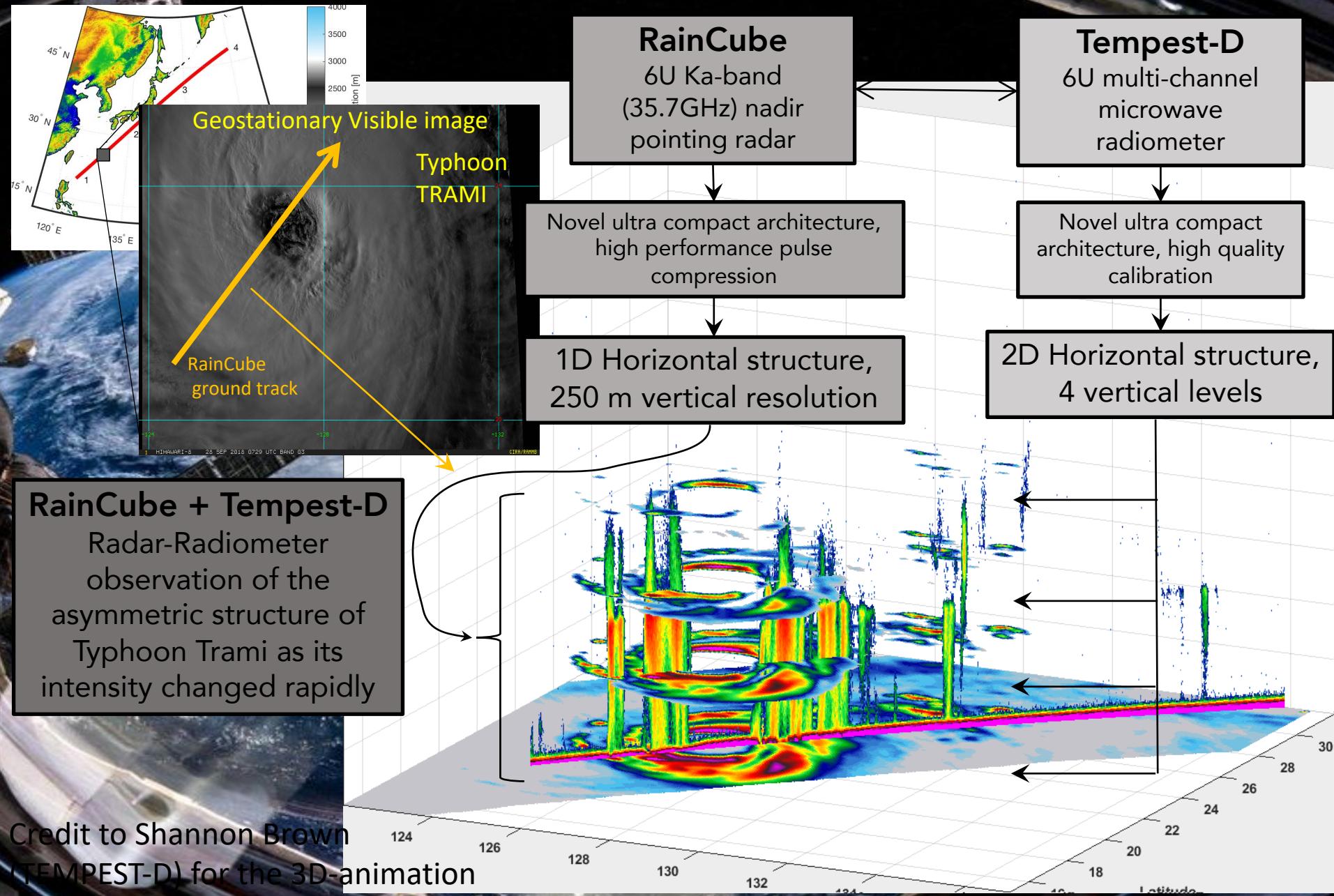
First successful operation in Nadir Pointing & first detection of rain over the Sierra Madre Oriental, near Monterrey, Mexico.
Fast growing orographic precipitation developed shortly before RainCube's pass which overflowed its north-eastern edge



RainCube and TEMPEST-D observe Typhoon Trami on Sept. 28, 2018

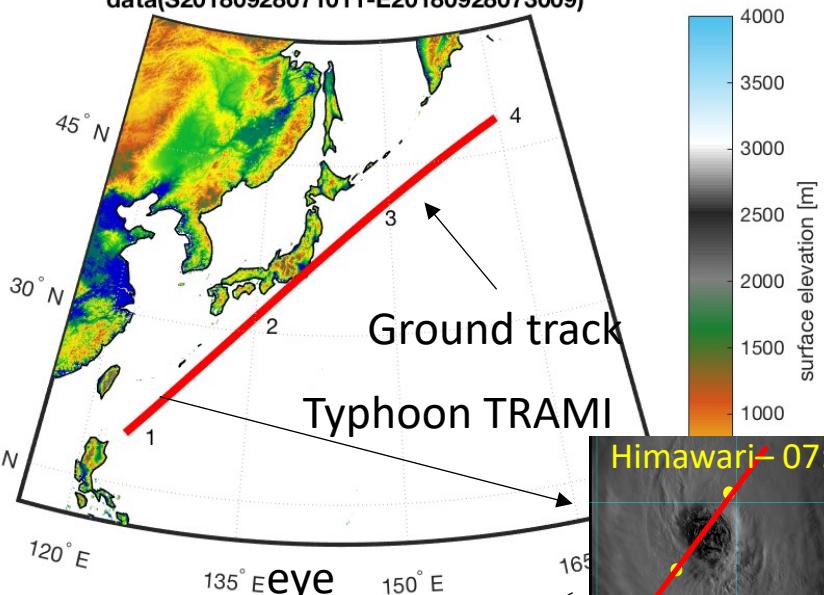


RainCube and TEMPEST-D observe Typhoon Trami on Sept. 28, 2018

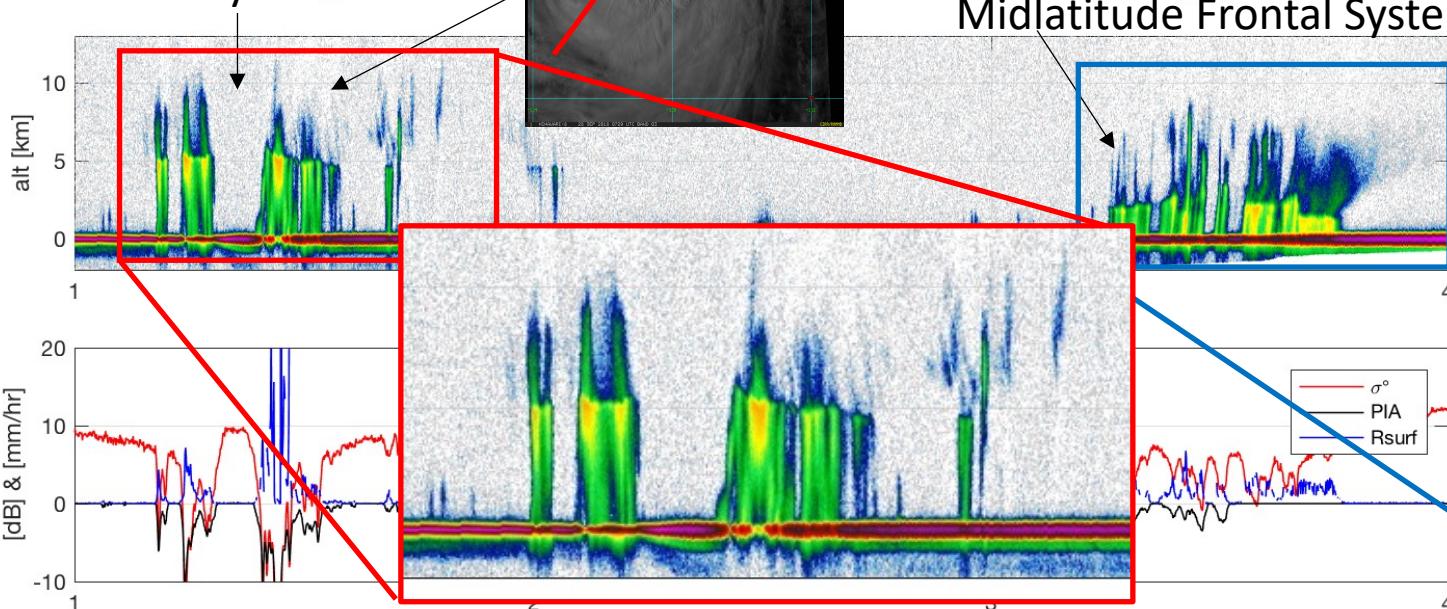
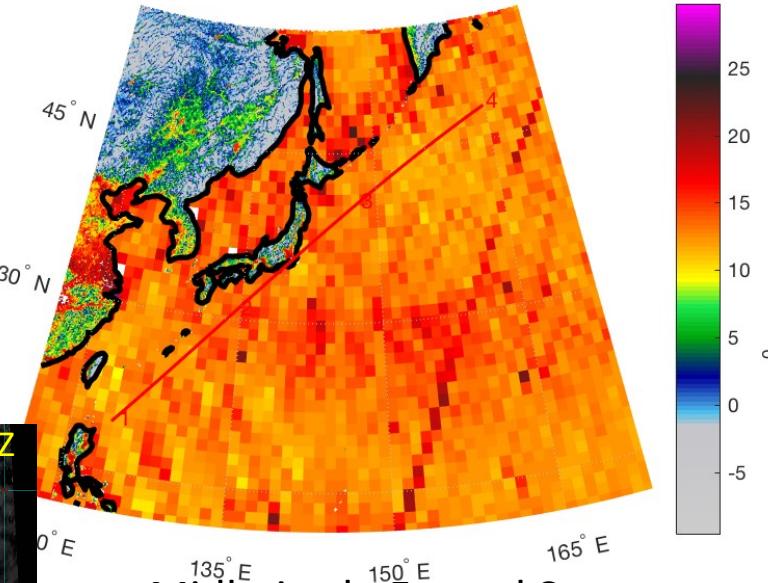


RainCube – September 28, 2018

CloudSat-DEM based on NASA-DEM
data(S20180928071011-E20180928073009)



GPM σ^0 reference
2018/9/28 @ 7:18:28 --> 2018/9/28 @ 7:30:10

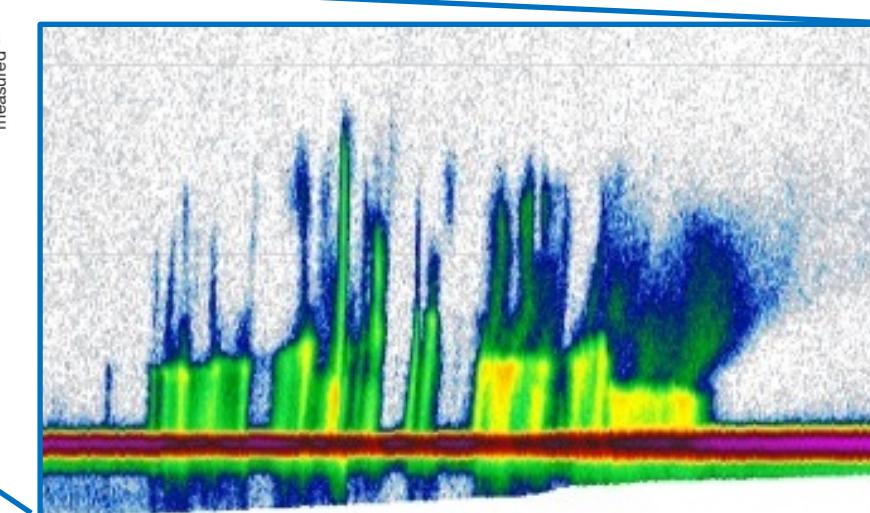


Structure of Typhoon TRAMI

Shortly after it had weakened from Cat 5 to Cat 2. The SW-NE cross section shows very little convective activity along the eyewall (mostly located in the SE sector at that time).

Mid-Latitude system with deep convection

The complex structure of this frontal system propagating NW from Japan includes deep convective towers reaching almost 9 km and sharp gradients of the zero isotherm height.

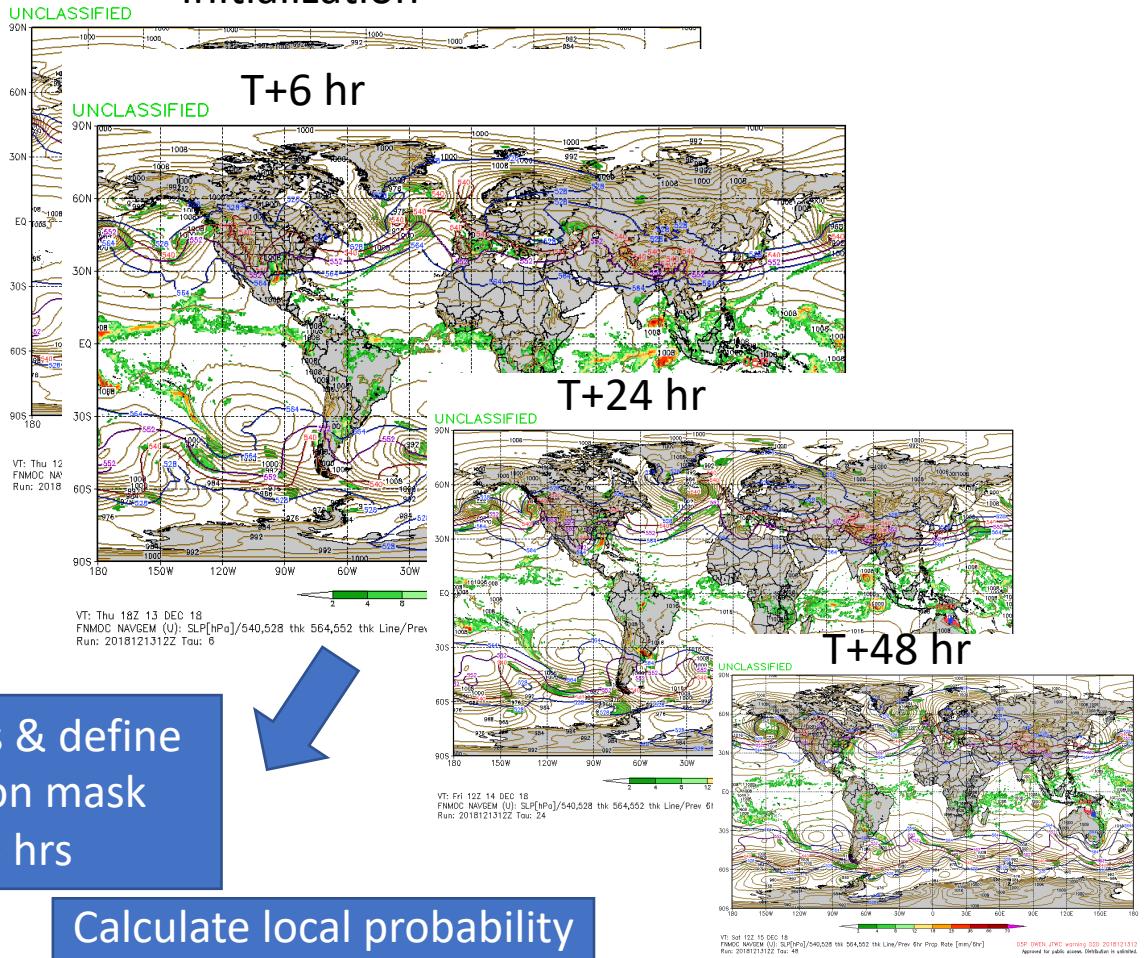


Science Operations Planning

Need to automate the planning of events in a prioritized way

- Constraints
 - Maximum of 6 20 minute Radar Acquisitions per day
 - Imposed by spacecraft power system
 - No operations on consecutive orbits
 - Imposed by spacecraft power system
 - No operations in umbra
 - Preferred because of higher occurrence of reboots in umbra
- Priorities
 - Forecasted presence of precipitation
 - CONUS – for NEXRAD
 - GPM – for DPR
 - Storms of interest

Initialization



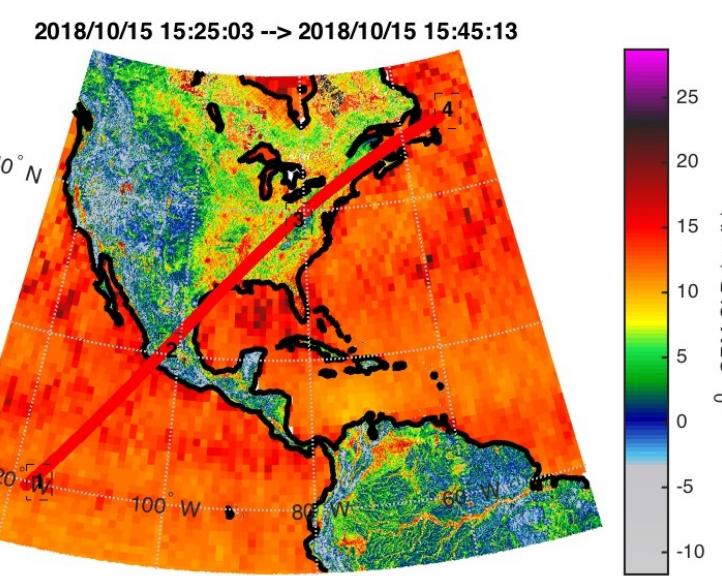
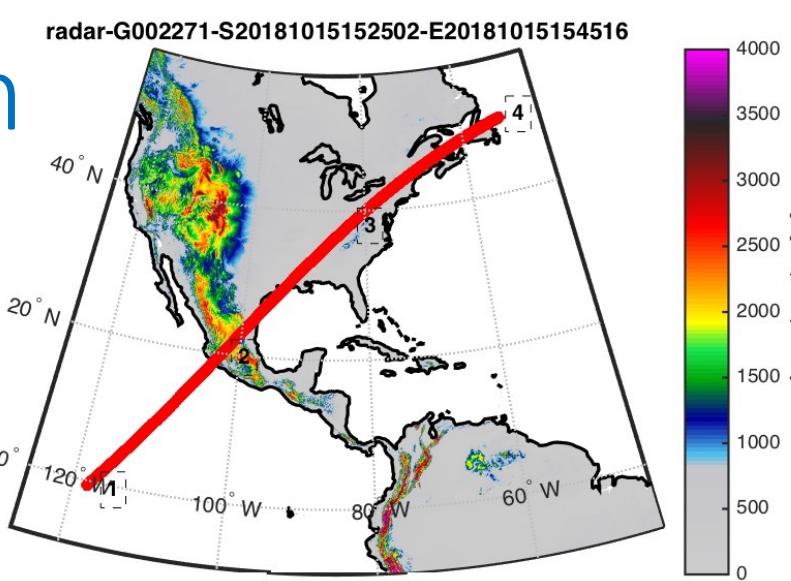
Parse images & define precipitation mask every 6 hrs

Calculate local probability of precipitation along the predicted orbit of RainCube

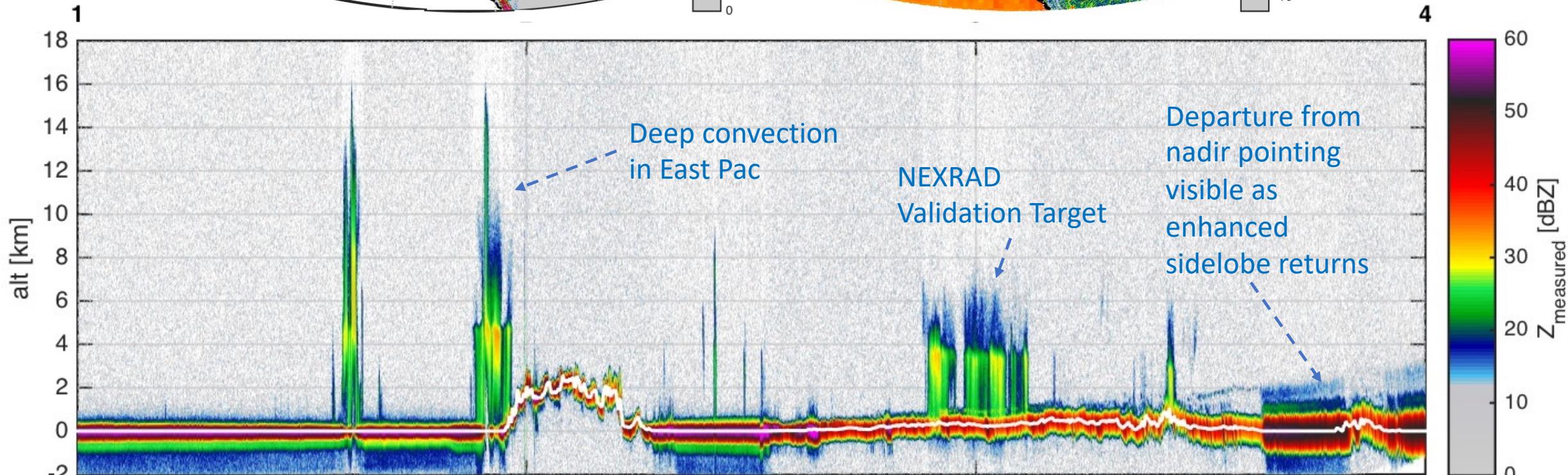
Prioritize close approaches with GPM and passes over GPM GV sites (CONUS, Japan, Australia)

Validation

High-resolution DEM from CloudSat



Surface reflectivity from GPM DB



time	15:25:03
lat	-0.6
lon	-118.1

15:31:46

19.7
-102.9

15:38:30

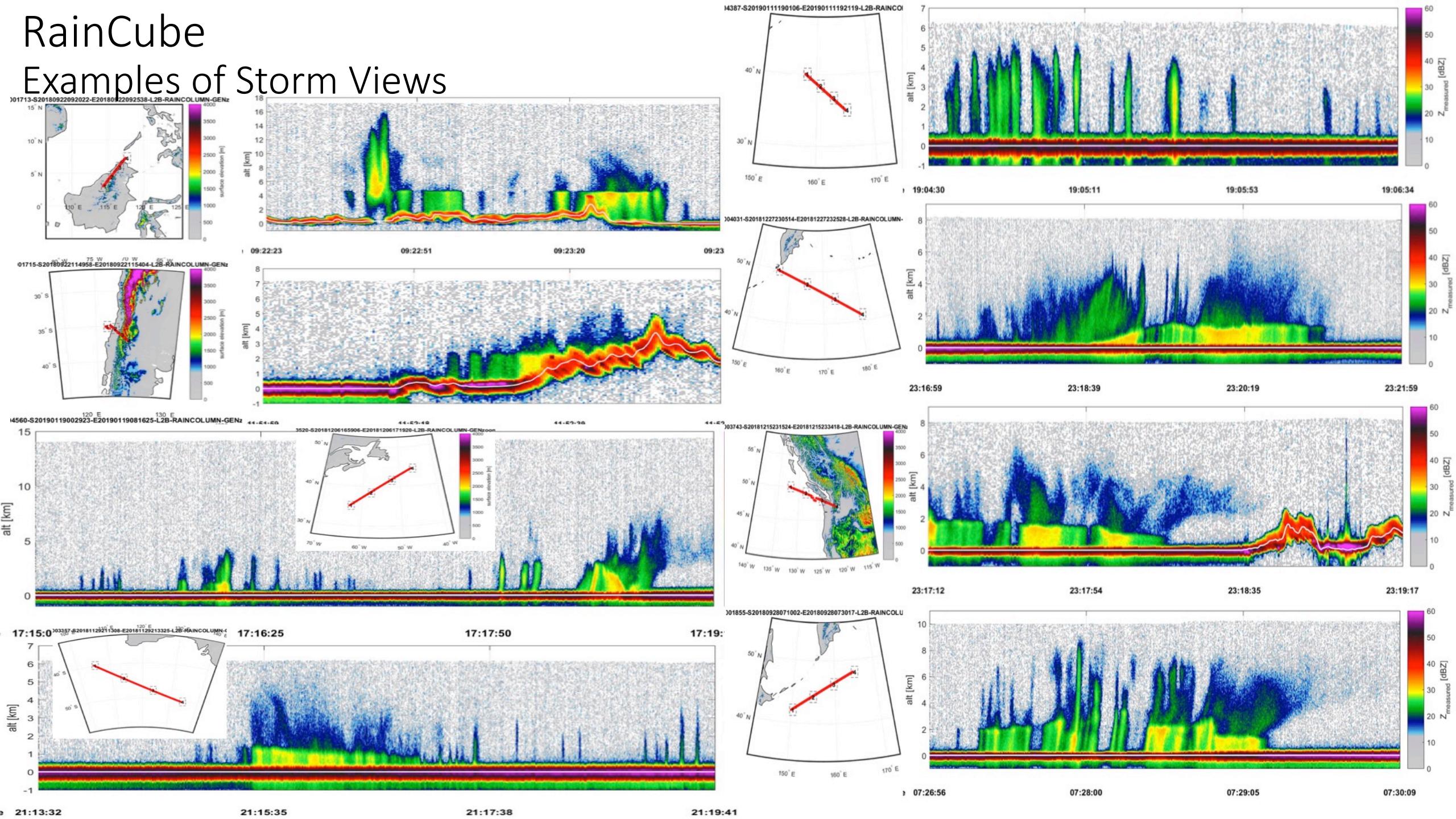
38.0
-83.0

15:45:13

50.1
-52.0

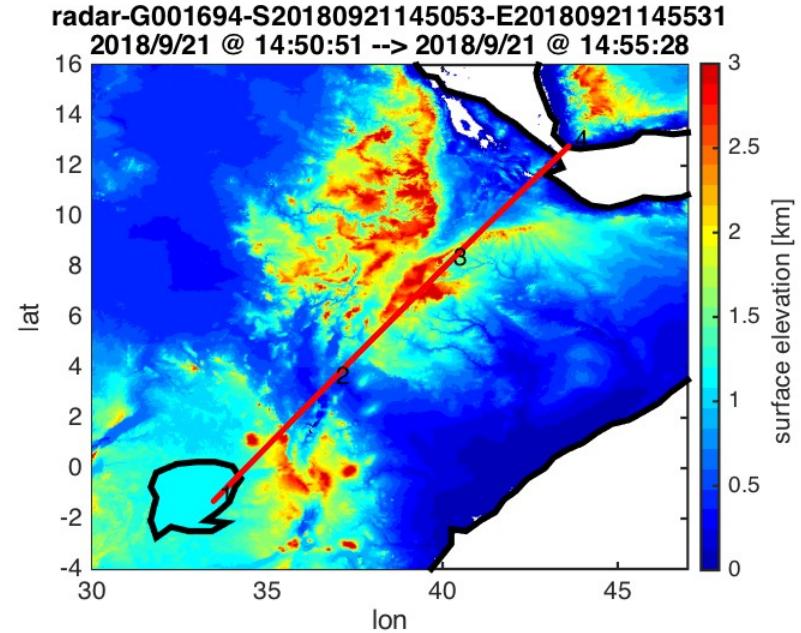
RainCube

Examples of Storm Views

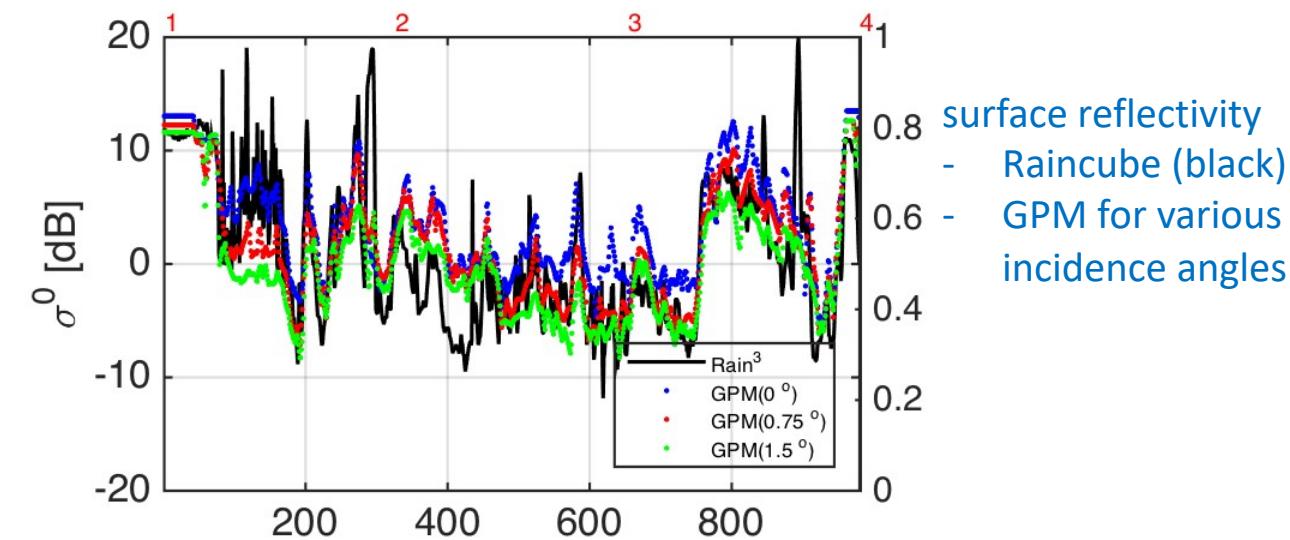
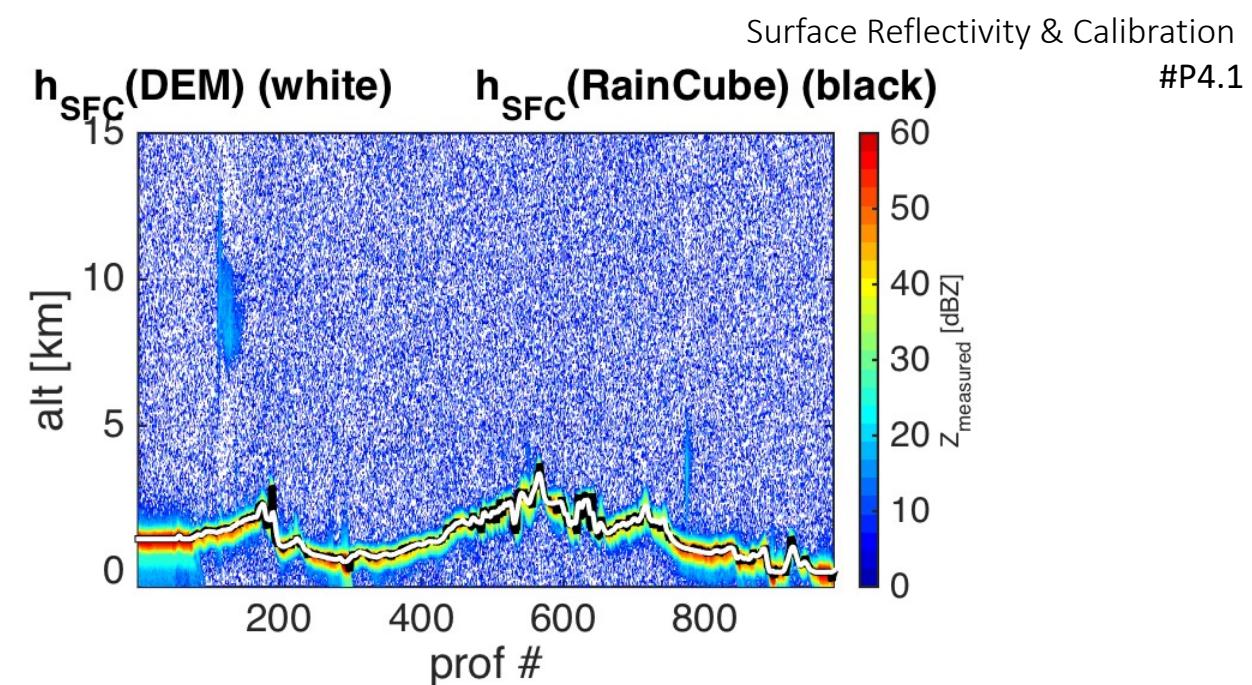
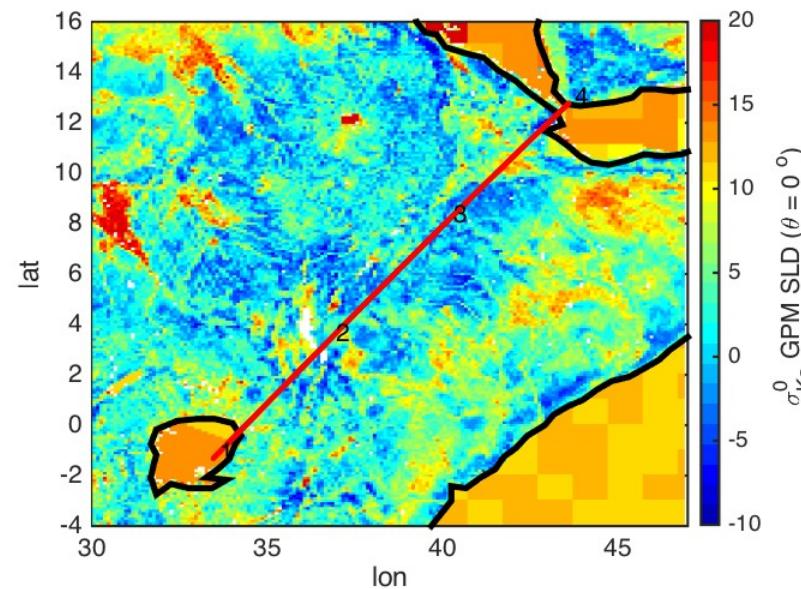


Surface reflectivity
(1/2) Horn of Africa/Red Sea

High-resolution DEM from CloudSat

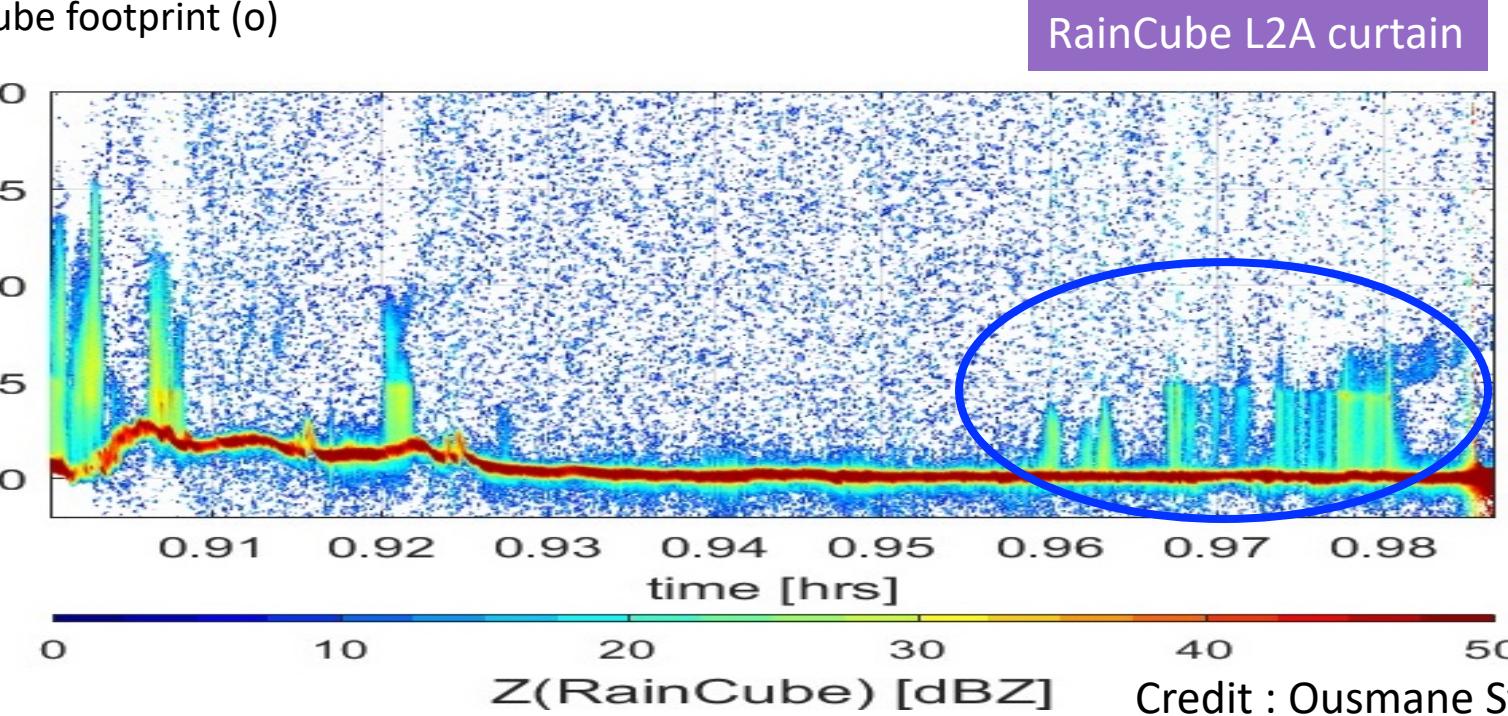
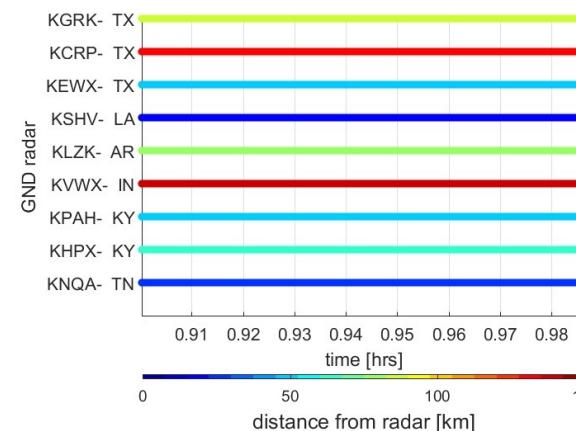
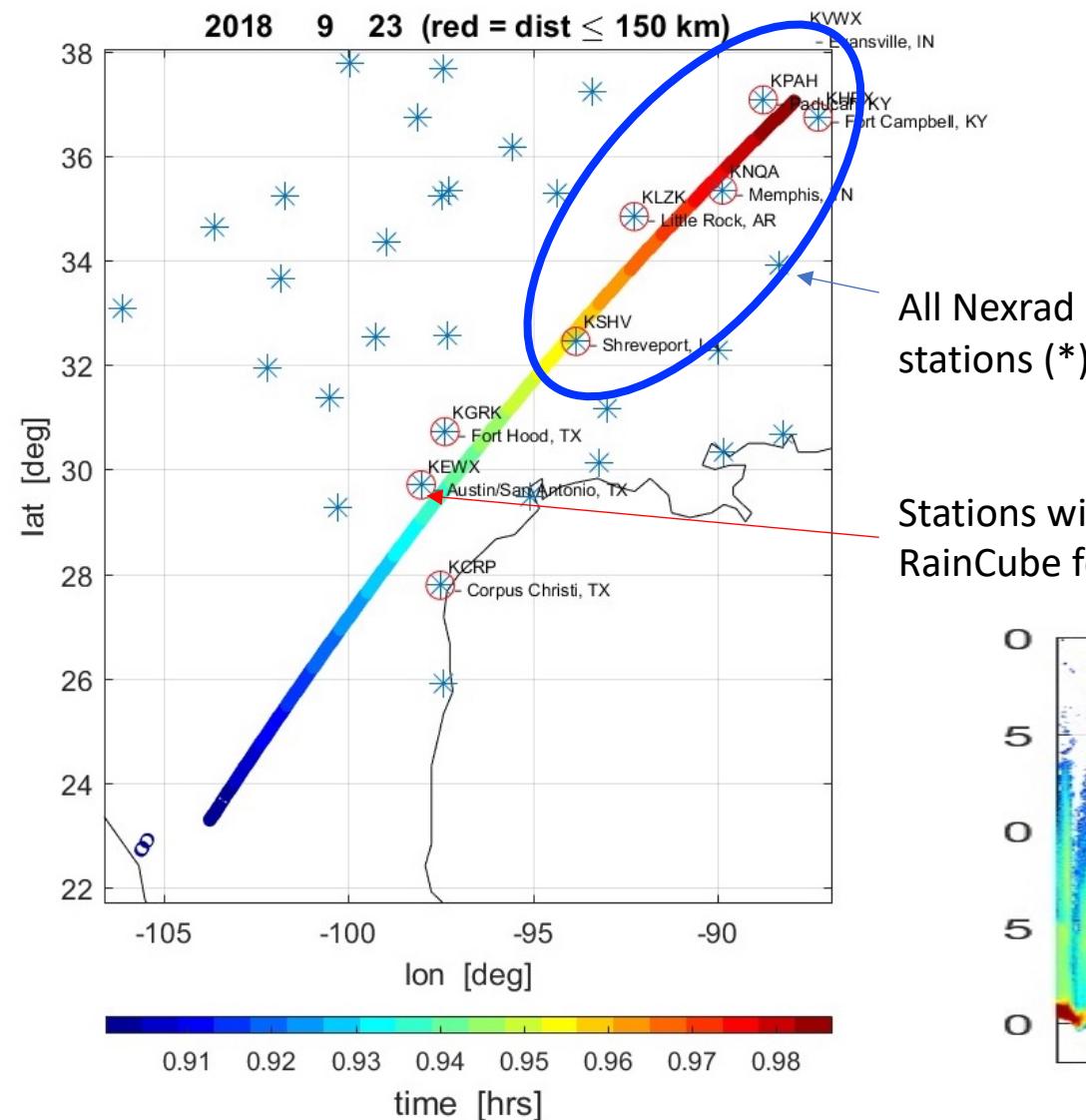


GPM surface reflectivity



Granule G001728: Memphis, TN; Little Rock, AR

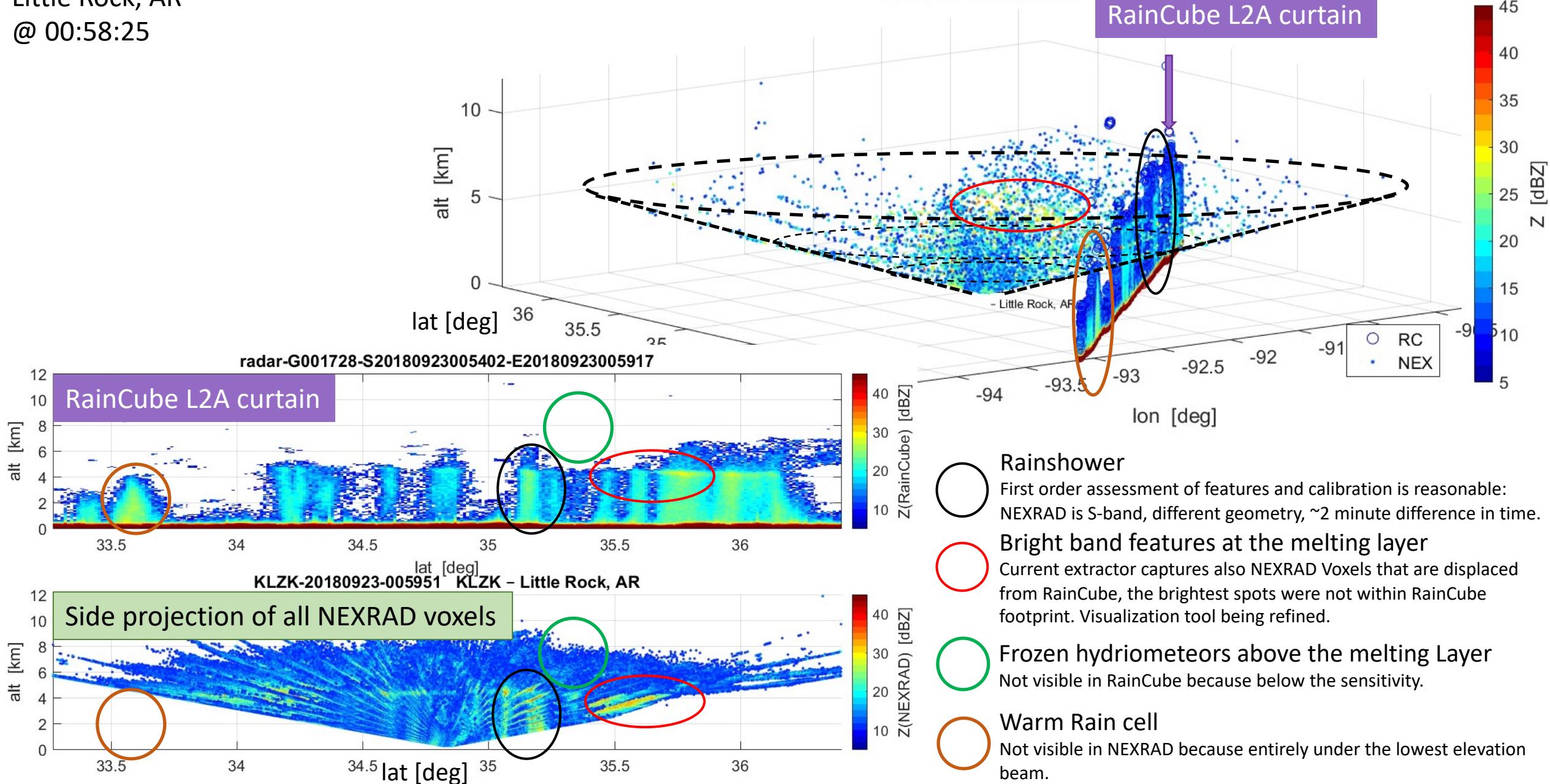
Validation



Granule G 001728: Memphis, TN; Little Rock, AR

L2A Validation - NEXRAD

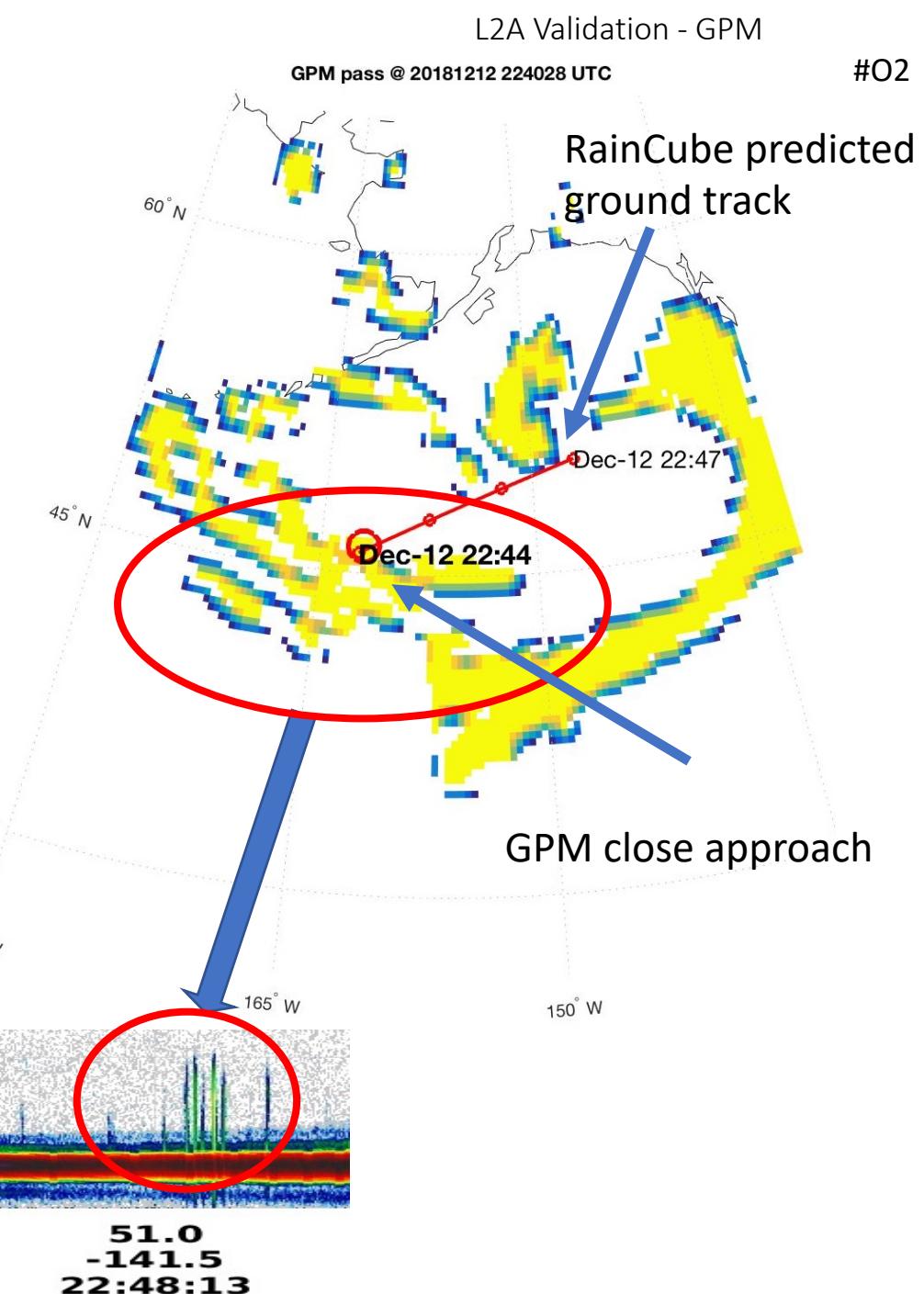
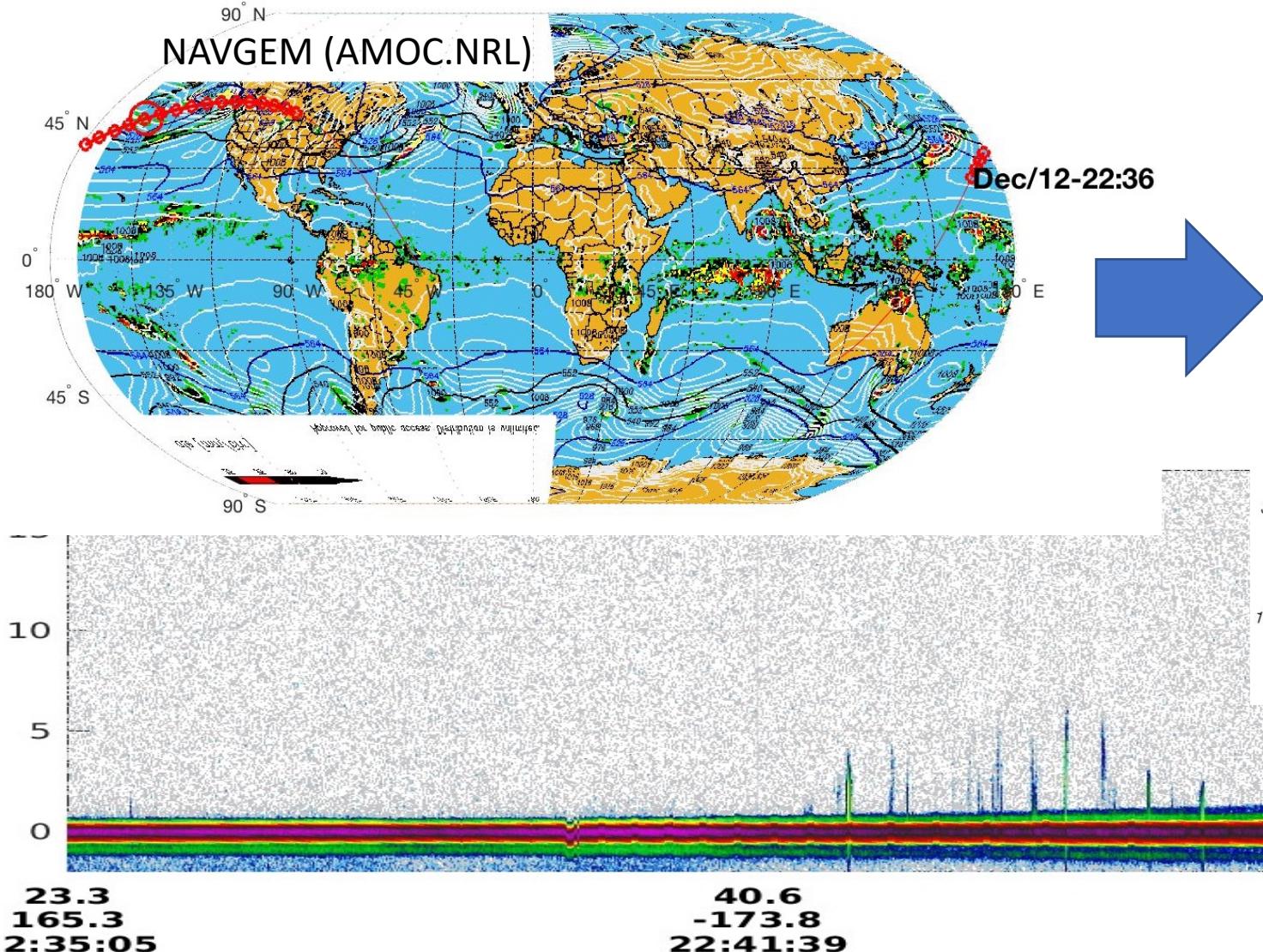
Little Rock, AR
@ 00:58:25



WEDNESDAY

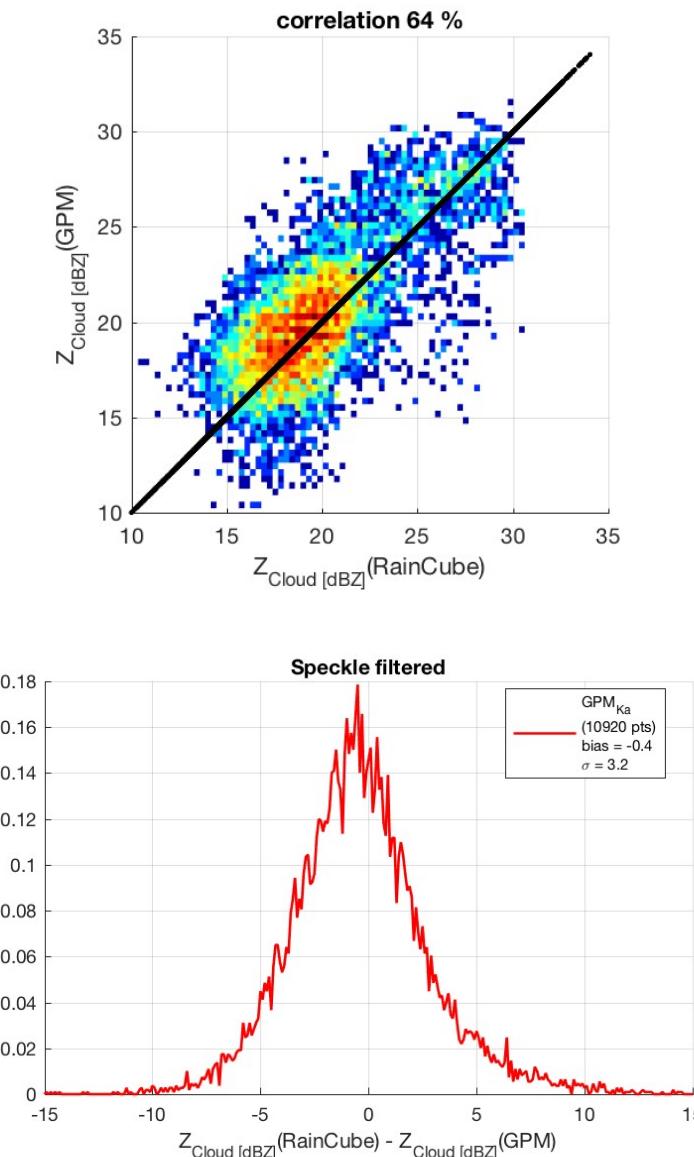
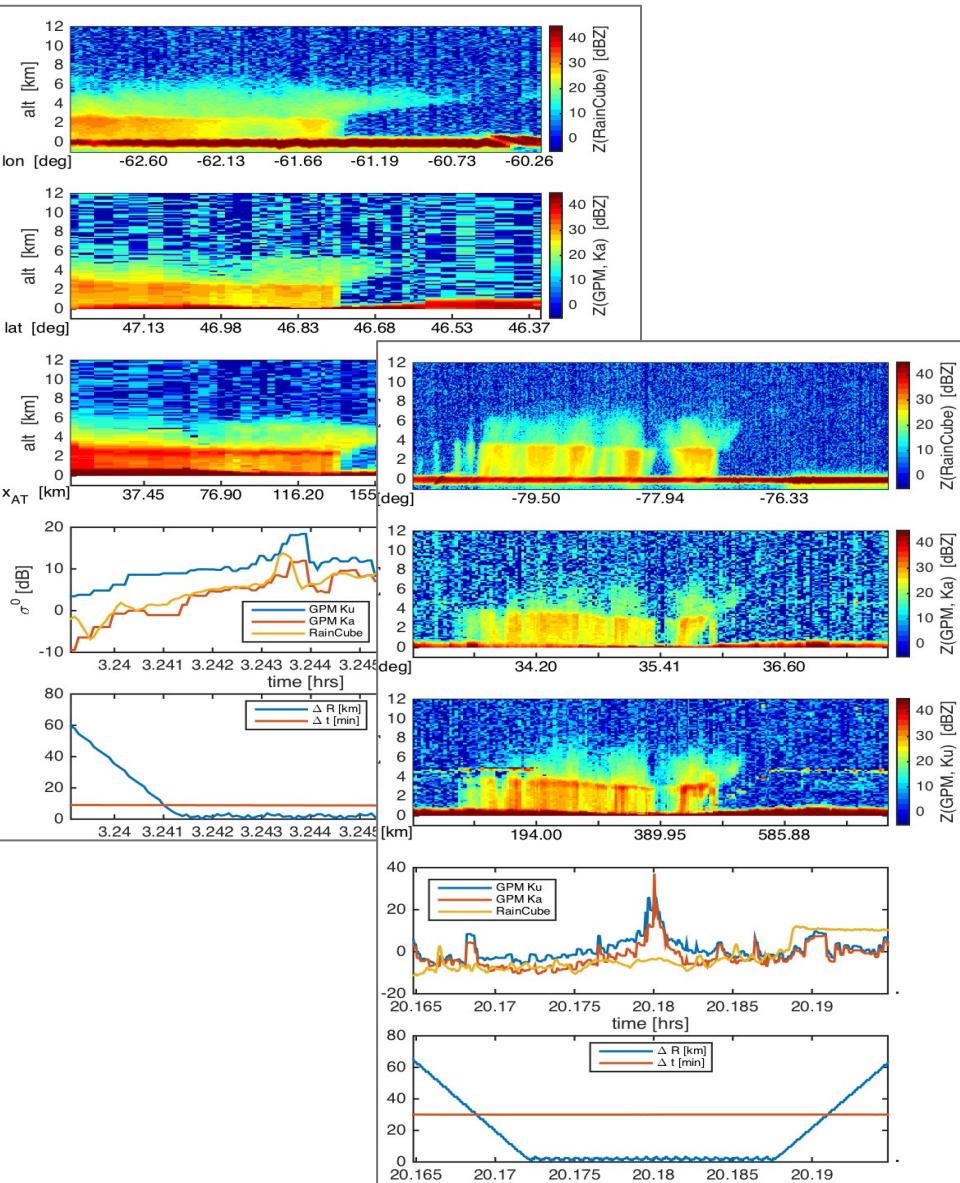
Dec 12

Tentative case with GPM over the North Pacific : GPM @ 2240Z, RC @ 2244Z.
High probability of precipitation, out of range of ground validation.



RainCube calibration

GPM/DPR-relative calibration validation



Current estimate of bias between DPR Ka and RainCube.

Two independent approaches indicate :

- a) $|Bias| < 1.5 \text{ dB}$
- b) $bias \ll \sigma$

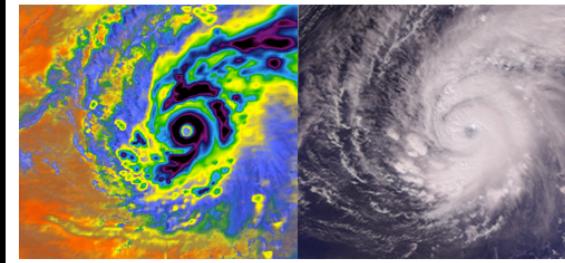
Outcomes:

- 1) no calibration correction planned for next public release of science data
- 2) Inclusion of this assessment in the product document for user awareness

TCIS portal hosts RainCube data



TROPICAL CYCLONE INFORMATION SYSTEM



Supertyphoon Pongsona struck the U.S. Island of Guam on Sunday, December 8, 2002. The composite image (left) of the supertyphoon was made by overlaying data from the infrared, microwave, and visible/near-infrared sensors that make up the AIRS sounding system. This storm can also be seen with the standard AIRS Vis/NIR (right).

Welcome to the JPL Tropical Cyclone Information System

The JPL Tropical Cyclone Information System (TCIS) was developed to support hurricane research. It has two components: a 12-year global archive of multi-satellite hurricane observations and, what was a near real-time portal, that supported the 2010 NASA Genesis and Rapid Intensification Processes (GRIP) hurricane field campaign. Together, data and visualizations from the near-real time system and data archive can be used to study hurricane process, validate and improve models, and assist in developing new algorithms and data assimilation techniques. Below you will find links to various portals where you can view different types of data.

- [◀ Introduction](#)
- [◀ Team](#)
- [◀ Collaborators](#)
- [◀ Funding](#)
- [◀ Publications](#)

Site Manager: Svetla M Hristova-Veleva

PRIVACY

The Tropical Cyclone Information System hosts RainCube data.

Huge thank you to PI : Svetla Hristova-Veleva, Site Administrator Quoc Vu, and Data Manager Brian Knosp)

L2A are posted (data & browse images).
L2B Data will be made public when QC is satisfactory.
No plan to open L0 and L1 data to the public.

JPL HOME | EARTH | SOLAR SYSTEM | STARS & GALAXIES | SCIENCE & TECHNOLOGY

BRING THE UNIVERSE TO YOU: [Twitter](#) [Facebook](#) [RSS](#) [Email](#)

TCIS Data Repository

Here you will find data files from the JPL Tropical Cyclone Information System's Data Repository. Data may also be available from TCIS campaign portals. For additional information, please visit <https://tropicalcyclone.jpl.nasa.gov>.

Name	Last modified	Size	Description
Parent Directory		-	
camp2ex/	2018-06-01 07:10	-	
cpx/	2018-06-12 20:42	-	
epoch/	2017-09-11 12:37	-	
hs3/	2018-06-27 20:04	-	
raincube/	2018-12-19 11:10	-	
shout/	2017-10-18 09:51	-	
TC Data Archive/	2018-06-29 10:02	-	

Site Manager: Svetla M Hristova-Veleva PRIVACY Webmaster: Quoc Vu (JPL Clearance: CL#08-3490)

PRIVACY



https://tcis.jpl.nasa.gov/data/raincube/L2A-GEOPROF_nc/2019/02/04/

PRIVACY



TCIS Data from the RainCube Mission

For additional information, please visit <https://www.jpl.nasa.gov/cubesat/missions/raincube.php>.

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Parent Directory		-	
radar_G004945_S20190204014005_E20190204020021_L2A-GEOPROF_v1-seg1.nc	2019-02-25 15:40	49M	
radar_G004945_S20190204014005_E20190204020021_L2A-GEOPROF_v1_seg1_zrls_map2.jpg	2019-02-25 15:40	466K	

Site Manager: Svetla M Hristova-Veleva PRIVACY Webmaster: Quoc Vu (JPL Clearance: CL#08-3490)

PRIVACY



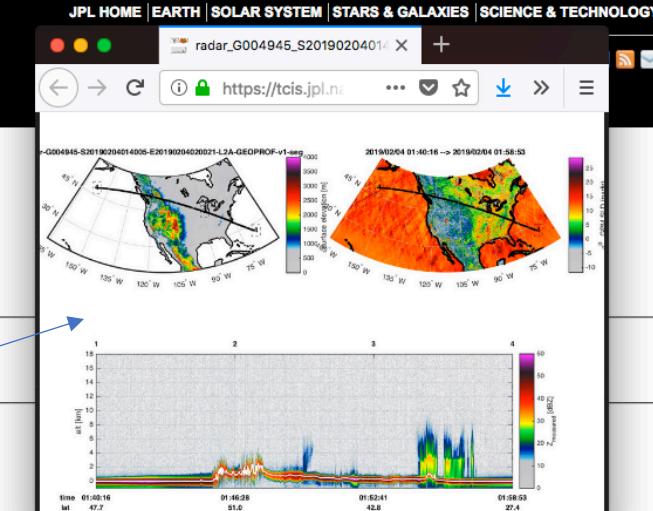
PRIVACY



Site Manager: Svetla M Hristova-Veleva

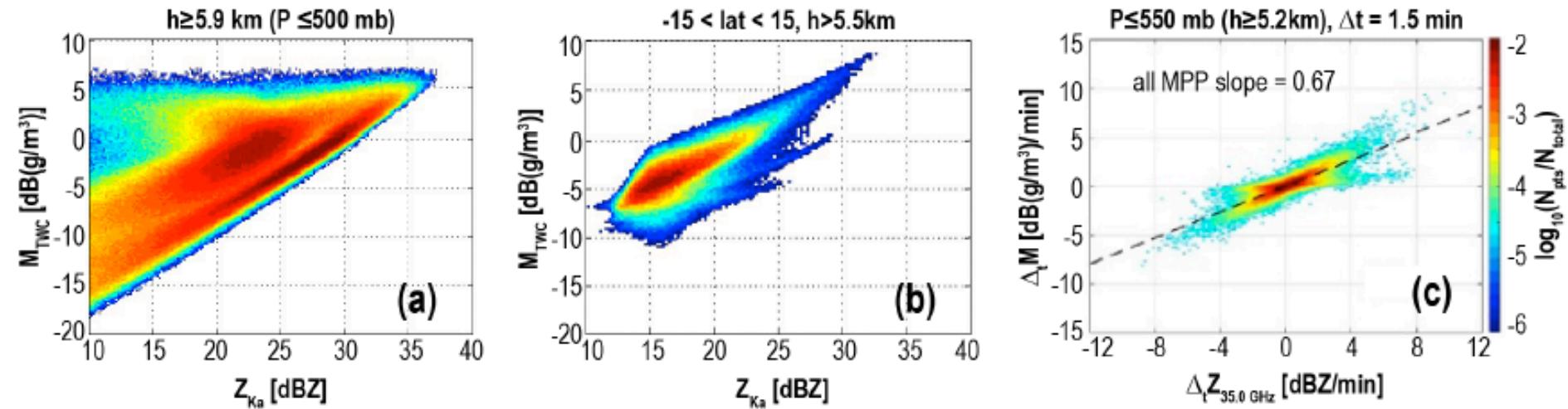
PRIVACY

Webmaster: Quoc Vu (JPL Clearance: CL#08-3490)



What's next ?

To target the original science need,
we need to deploy more than one...



Time difference Ze measurements more directly relate to time change of condensed mass (M) than does Z relate to M (a) Ze-M relationship above 5.9km from simulations of a tropical storm by a CRM with four different versions of microphysical schemes. (b) The Ze-M relation where the coefficients are regionally tuned to M retrieved by GPM product for a 5-day period (4–8 August 2015). The difference between (a) and (b) illustrates the anticipated effect of including GPM-based a priori data to constrain the Ze-M relationships. (c) The $\Delta_t Z - \Delta_t \ln M / dt$ relationship above 5.2km derived from the CRMDB applied to multiple cloud physical schemes.

See also:

1. Haddad, Z.S., O.O. Sy, S. Hristova-Veleva, G.L. Stephens; *Derived Observations from Frequently-Sampled Microwave Measurements of Precipitation. Part I: Relations to Atmospheric Thermodynamics*. *IEEE Trans. Geosci. Rem. Sens.* vol. 55, pp. 2898-2912, 2017
2. Sy, O.O.; Haddad, Z.S.; Stephens, G.L.; Hristova-Veleva, S.; *Derived Observations from Frequently-Sampled Microwave Measurements of Precipitation. Part II: Sensitivity to Atmospheric Variables and Instrument Parameters*. *IEEE Trans. Geosci. Rem. Sens.*, pp. 1-13. 2017

What's next ?

- Constellation of RainCube's "as is"

- Analyze the current dataset to demonstrate the potential and the limitations of the current system in addressing specific science questions.

- Constellation with a larger/scanning antenna

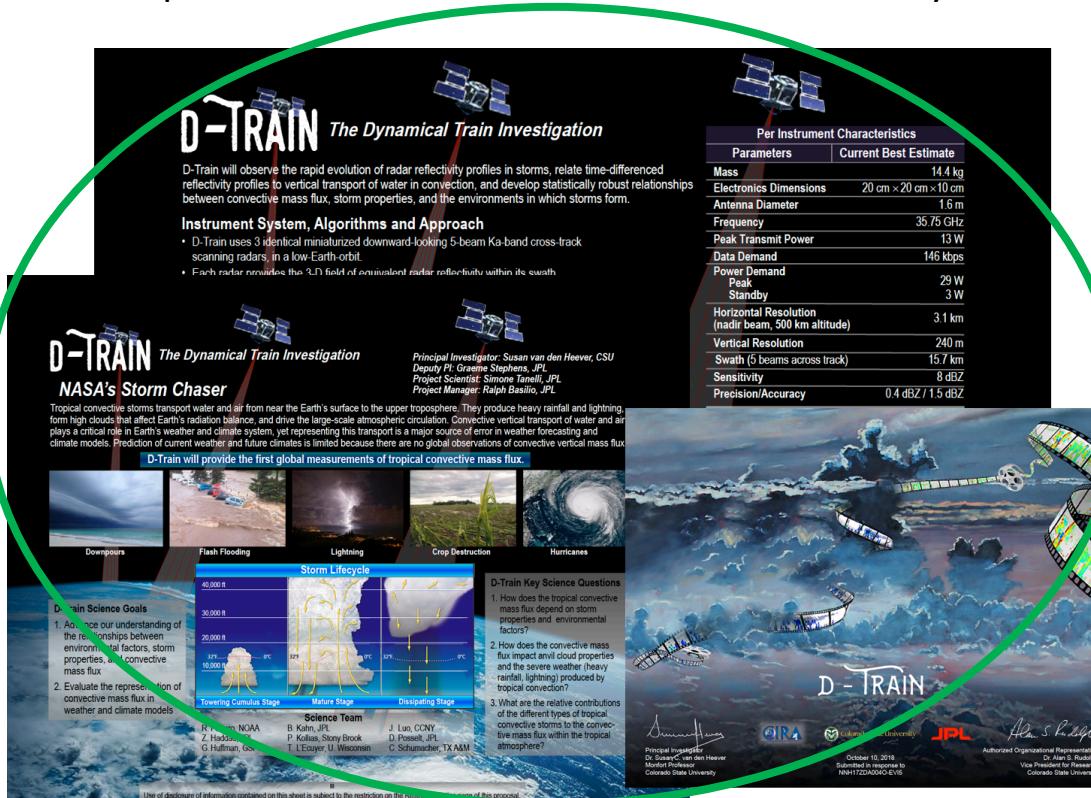
- To address a larger set of science questions
- Development of **technologies** and of **mission concepts** is ongoing

- Constellation with other Radars and Radiometers:

- A study team in the Earth Science Decadal Survey 2017 will consider RainCube-like constellations for measurements of convection and precipitation
- Higher frequency versions of RainCube for cloud and water vapor observations

- Planetary applications

- An evolution of this instrument could support altimetry and cloud and precipitation on planetary targets



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Proceedings OF THE IEEE

SPECIAL ISSUE
Small Satellites

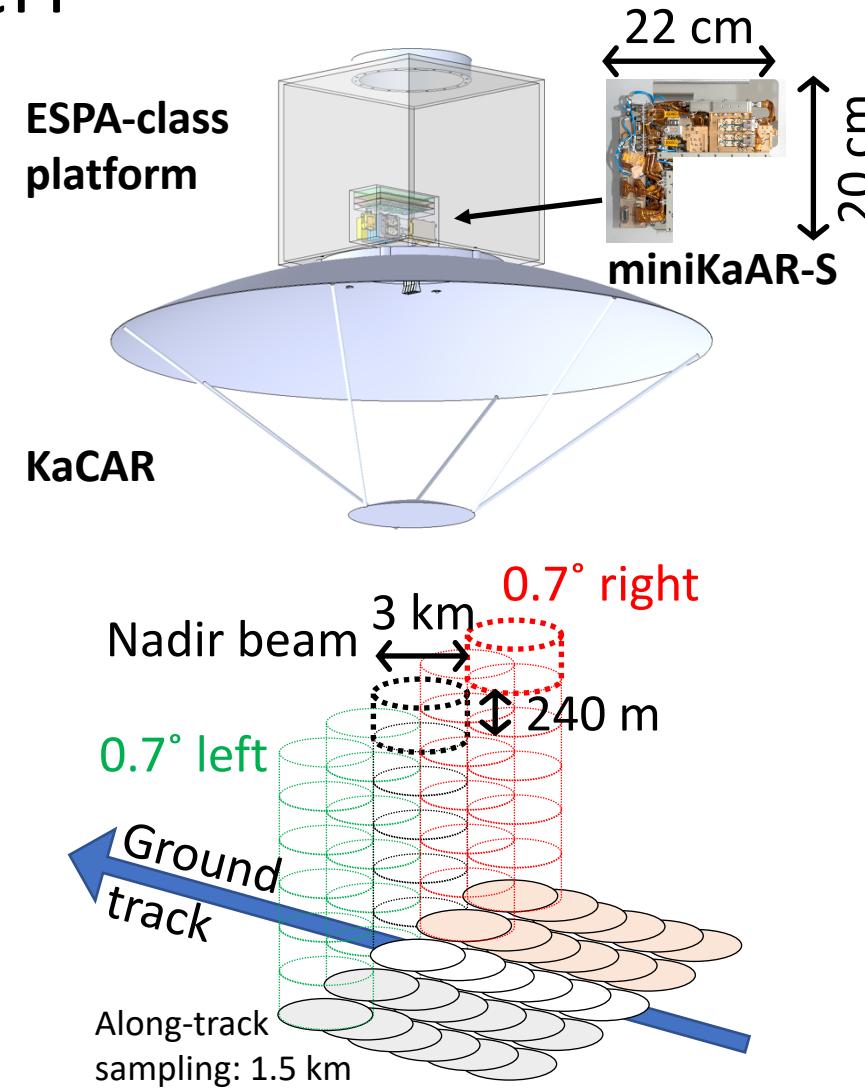
Point of View: How Is the Networked Society Impacting Us?
Scanning Our Past: Who Invented the Earliest Capacitor Bank ("Battery" of Leyden Jars)? It's Complicated



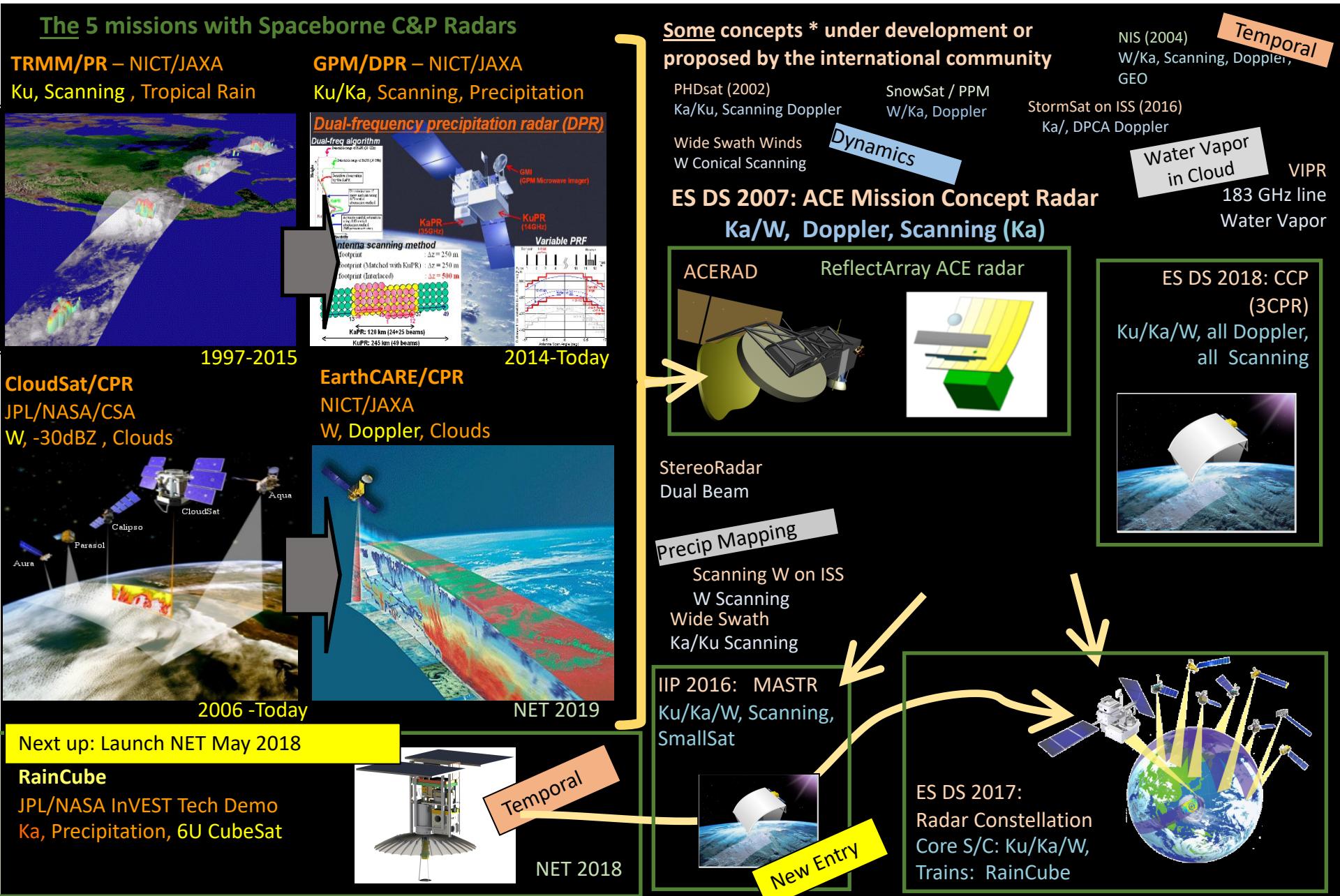
Ka-band ESTO InVEST and ACT programs

	6U	12 U	50 kg
Antenna size [m]	0.5	1.0	2.0
Sensitivity [dBZ]	15	5-10	0-5
Hor Resolution [km]	8	4	2
Range Res [m]			250
Beams	1	1-3	1-5
RF Power [W]	10	10-20	10-40

D-Train swath



* Pre-Decisional Information – For Planning and Discussion Purposes Only

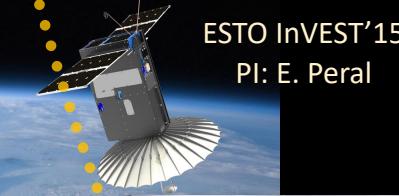
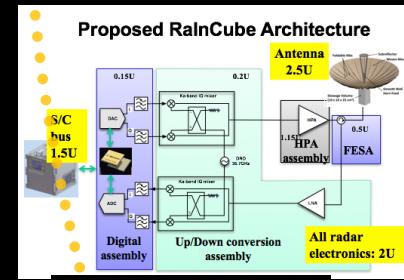


Precipitation and Cloud Radars for Small Satellites



NASA Jet Propulsion Laboratory
California Institute of Technology

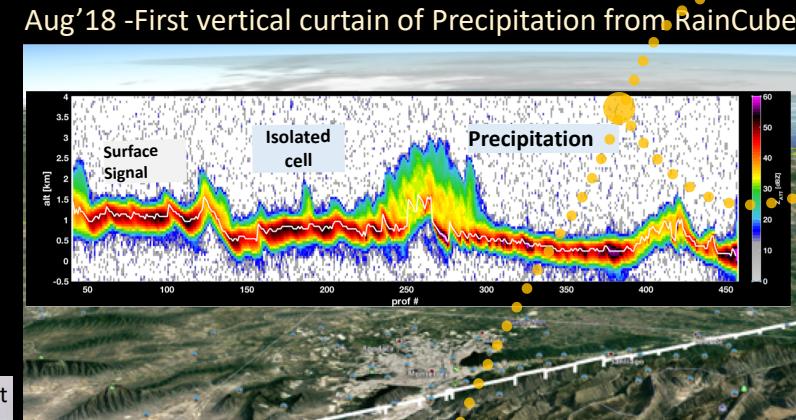
2013 – Initial Concept: Ka-band profiling radar to fit in a 6U spacecraft
High Gain Ultra Compact deployable antenna
Novel Radar Architecture
High Performance Pulse Compression



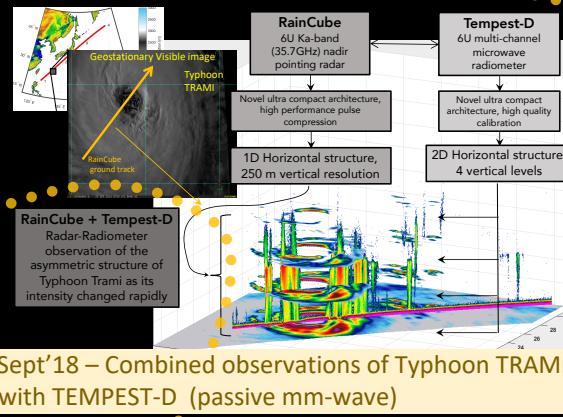
Feb'18 – Complete integration at Tyvak and delivery to Nanoracks



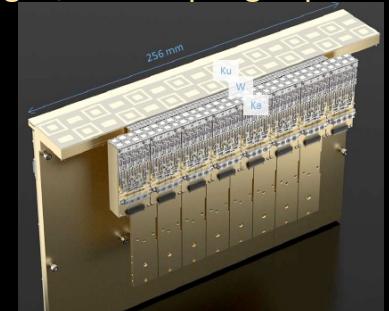
May'18 – Launch from Wallops Flight Facility



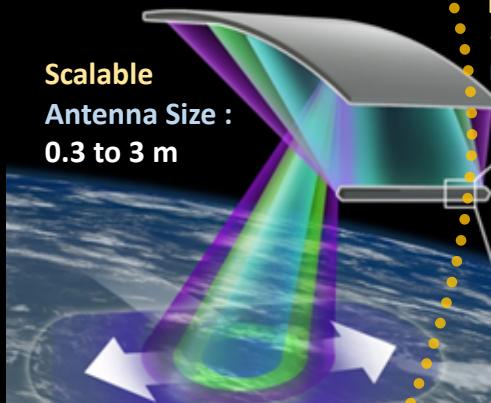
RainCube back end
Digital and Up-Down RF Conversion
reduce # of parts, simple



ACE 3CPR front-end (*)
singly-curved parabolic antenna and line feed array electronic cross-track scanning at Ku-/Ka-/and W-band
Agile, 3D sampling capability



Multi-Application SmallSat Tri-band Radar (MASTR) (*)
Ku-/Ka-/W-band electronically scanning



ESTO IIP – 2017/19
airMASTR
PI: M. Sanchez-Barbetta

RainCube & MASTR enable concepts of constellations of Small Satellites with Active and Passive microwave instruments (*)

(*) = Pre-Decisional Information -- For Planning and Discussion Purposes Only
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Airborne Precipitation and Cloud Radar 3rd Generation

APR-3 supports the science of GPM, CloudSat, ACE, CCP, RainCube, SWOT.

ACR (1996)

- W-band 94.9 GHz
- Doppler & Dual Pol



APR2 (2001)

- Ku- 13.4 GHz & Ka- 35.6 GHz
- Scanning: +/- 25° cross track
- Doppler & Depolarization

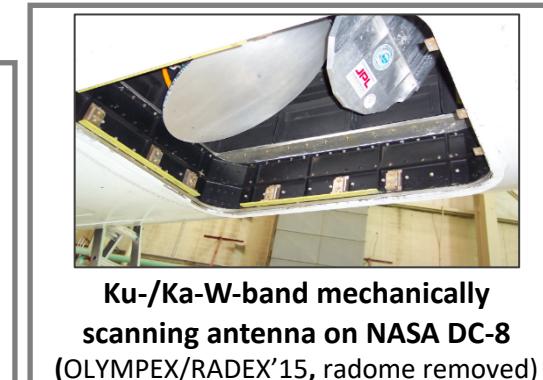
APR-3

APR3 on P-3
ORACLES 2016-2018



Ku+Ka+W
Scanning,
Doppler,
Dual Pol

Green: Ka- high sensitivity fixed ~3° width, "nadir"
Blue: W- high sensitivity fixed ~1° width, "nadir"
Orange: Ku-Ka-W-band matched scanning beam ~5° width, ±25° scan
30 m range sampling

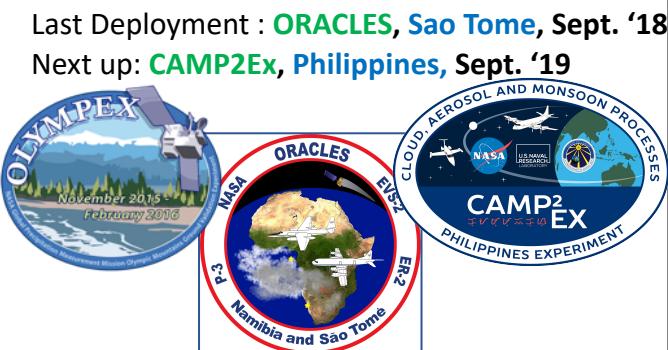


Ku-/Ka-W-band mechanically scanning antenna on NASA DC-8
(OLYMPPEX/RADEX'15, radome removed)



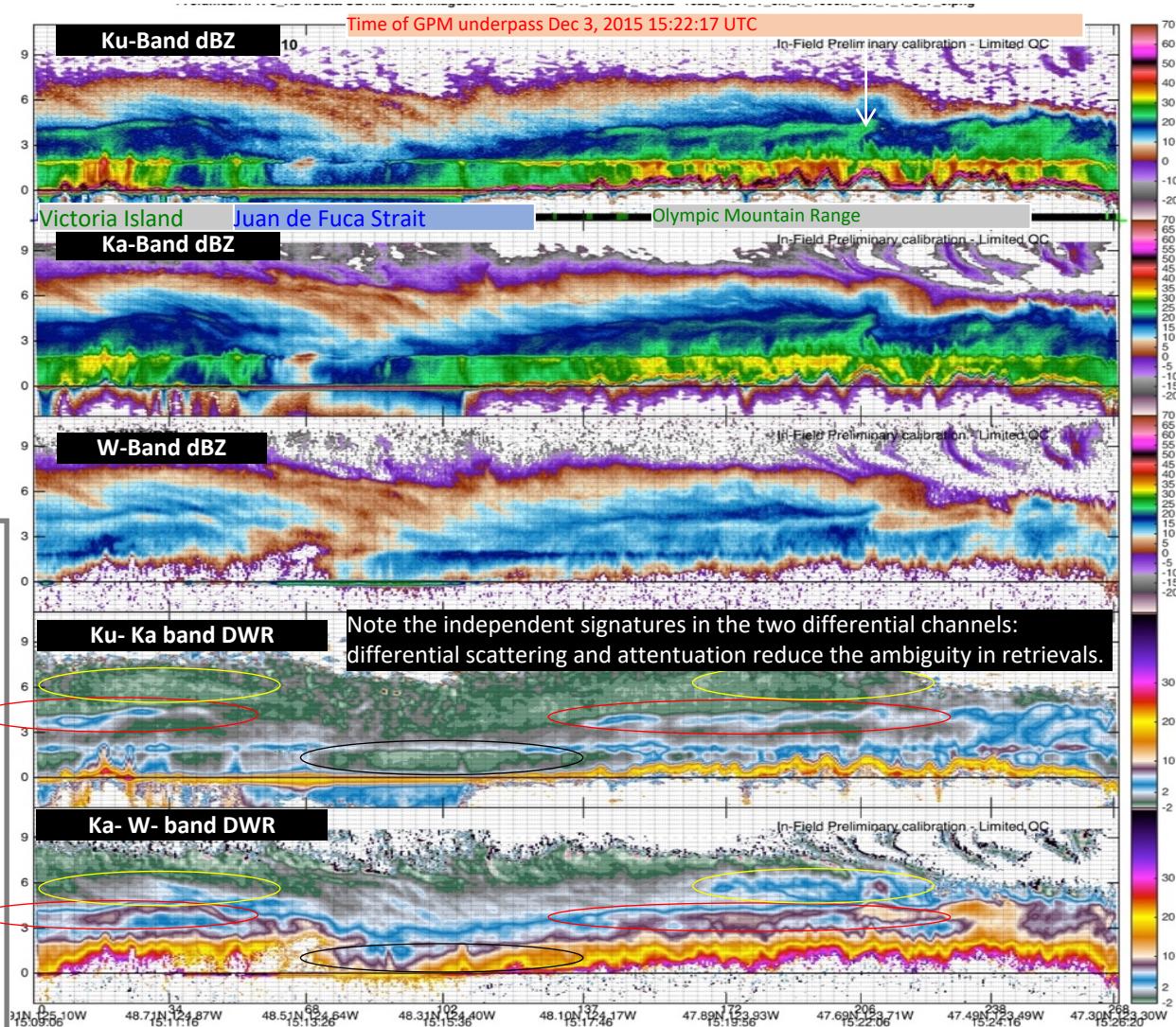
2018 Digital Subsystem by RSS
Replaces two separate and obsolete digital systems for increased signal generation and processing capability.

2018 W-band RF
Completely new low power chains and new housing. ~50% mass & volume reduction. Interfaces with new digital.



Last Deployment : **ORACLES, Sao Tome, Sept. '18**

Next up: **CAMP2Ex, Philippines, Sept. '19**



Example of Multi-frequency Radar Observations of Clouds and Precipitation
being used by GPM, ORACLES, RainCube, EarthCARE, ACE and CCP study groups

Multi-Application SmallSat Tri-band Radar (MASTR)

Pre-Decisional Information -- For Planning and Discussion Purposes Only

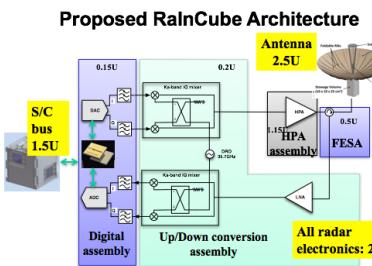
What's next ?

miniKaAR
back end
reduce # of parts
Simple

+

3CPR
antenna scheme
scanning
Agile

Proposed RainCube Architecture



The diagram illustrates the proposed RainCube architecture. It shows the S/C bus (1.5U), miniKaAR back end (0.15U), Antenna (2.5U), Digital assembly (0.2U), Up/Down conversion assembly (0.2U), and the HPA assembly (0.5U). The FESA (Flight Electronics Subsystem) is also indicated. All radar electronics are contained within a 2U volume.

Airborne Prototype airMASTR

ESTO IIP – 2017/19 – PI: M. Sanchez-Barbetta

Planned first flight : **Nov 2019**

Reflector (3CPR EM)
NASA DC-8 Pressure box (same position as APR-3)
Phased Array Feed (30 x 4 x 20 cm)

Low Bandwidth Mode: **High Bandwidth Mode:**

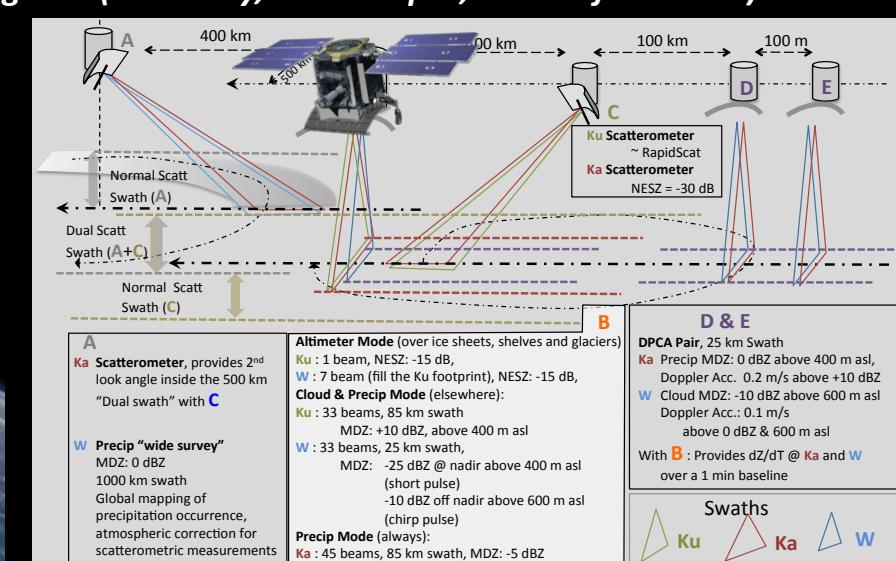
Antenna Size 1 to 3 m

high sensitivity (*Clouds and Precipitation, Scatterometry*)
high range res (*Altimetry, Snow Depth, Sea Ice freeboard*)

Antenna Size 1 to 3 m

Antenna Beam Coverage (Ku ALAF, W ALAF, Ka ALAF)

Scatterometer Modes



The diagram shows the satellite in space with various ground stations labeled A through E. The Ku scatterometer (RapidScat) has a 400 km swath (A). The Ka scatterometer (NESZ = -30 dB) has a 100 km swath (D & E). The W scatterometer has a 1000 km swath (W). The diagram also shows Normal Scatter Swath (A), Dual Scatter Swath (A+C), and Normal Scatter Swath (C).

Scatterometer Modes

A **Ka Scatterometer**, provides 2nd look angle inside the 500 km

B **D & E** DPCA Pair, 25 km Swath

C **Altimeter Mode** (over ice sheets, shelves and glaciers)

D **Precip MDZ:** 0 dBZ above 400 m asl, Doppler Acc. 0.2 m/s above +10 dBZ

E **Cloud & Precip Mode** (elsewhere):

F **W** **Precip "wide survey"** MDZ: 0 dBZ 1000 km swath Global mapping of precipitation occurrence, atmospheric correction for scatterometric measurements

G **Ku** **Scatterometer ~ RapidScat** NESZ: -15 dB, Cloud & Precip Mode (always): MDZ: +10 dBZ, above 400 m asl

H **W** **Scatterometer** MDZ: -25 dBZ @ nadir above 400 m asl (short pulse) -10 dBZ off nadir above 600 m asl (chirp pulse)

I **Ka** **Scatterometer** MDZ: -5 dBZ

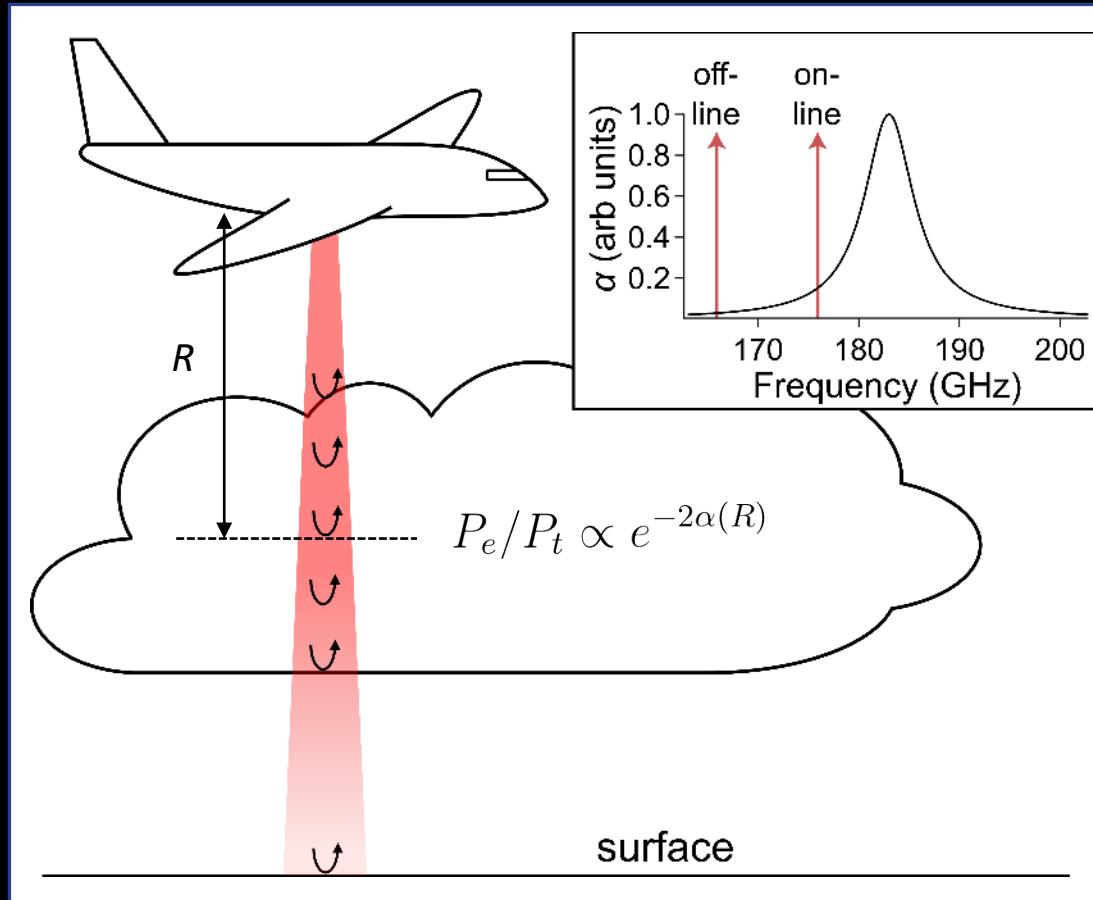
J **W** **Scatterometer** MDZ: -10 dBZ & 600 m asl With **B** : Provides dZ/dT @ **Ka** and **W** over a 1 min baseline

Ku **Ka** **W**

Vapor In-cloud Profiling Radar (VIPR)

Pre-Decisinal Information -- For Planning and Discussion Purposes Only

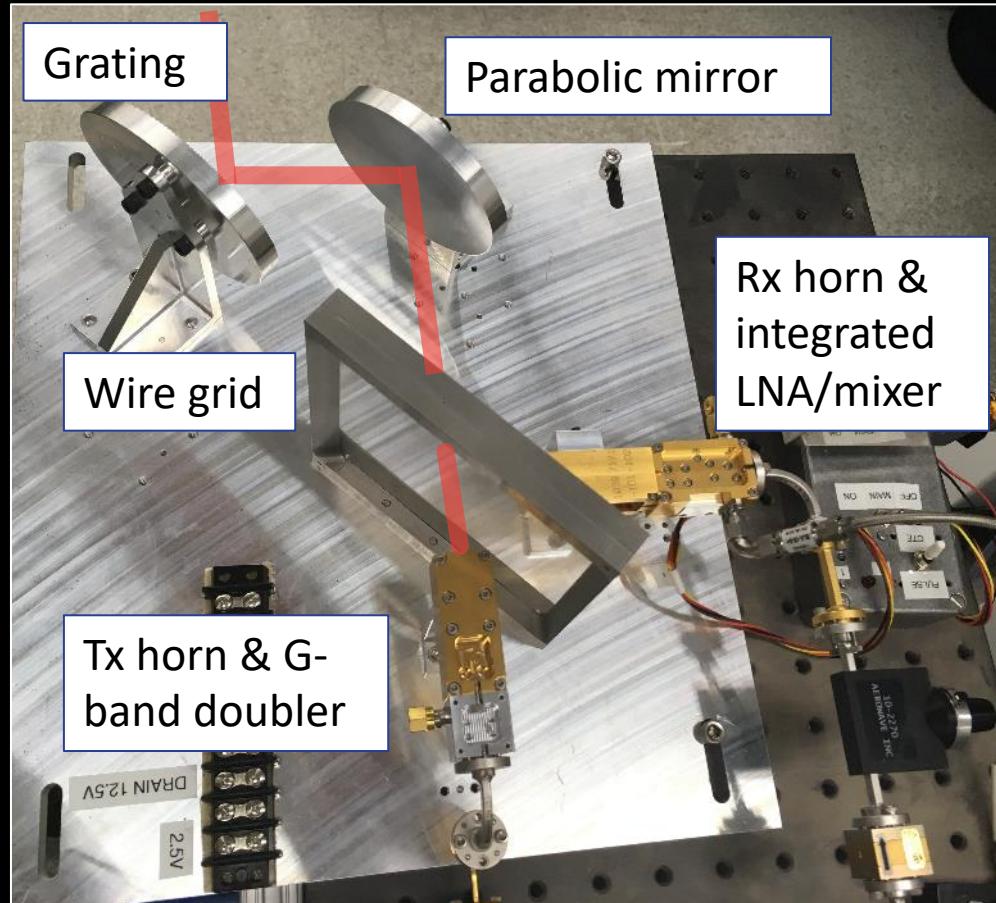
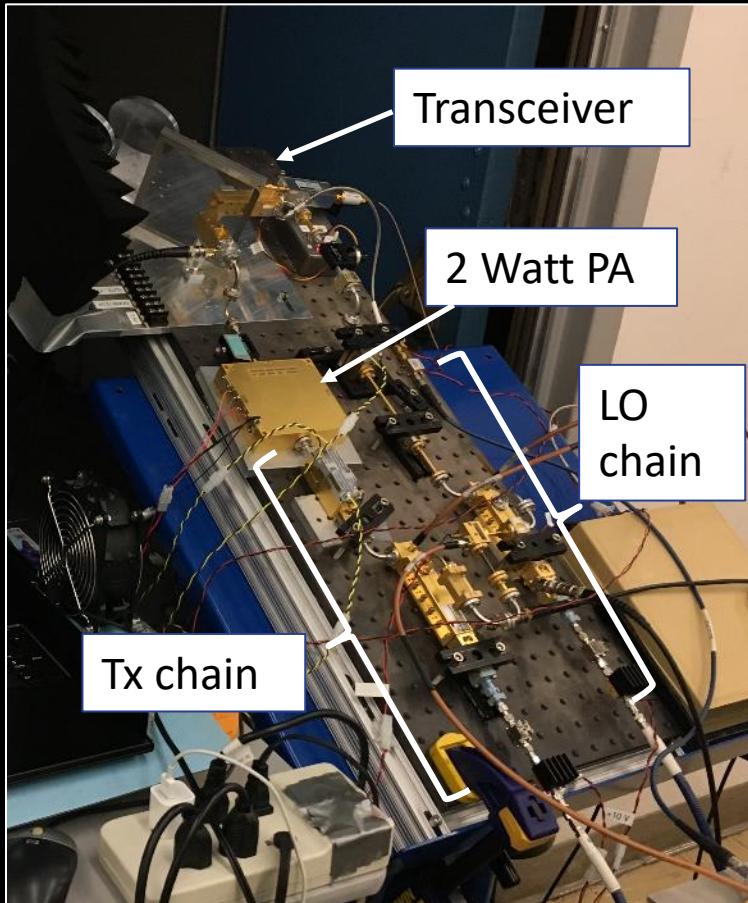
- Use widely tunable transmitter with ~ 500 mW transmit over $\sim 5\%$ bandwidth
- *Important assumption:* Reflectivity and extinction from hydrometeors independent of frequency
- Frequency dependence from hardware cancels out (common mode)
- Airborne platform demo → Surface echoes (total column water)



Vapor In-cloud Profiling Radar (VIPR)

Pre-Decisinal Information -- For Planning and Discussion Purposes Only

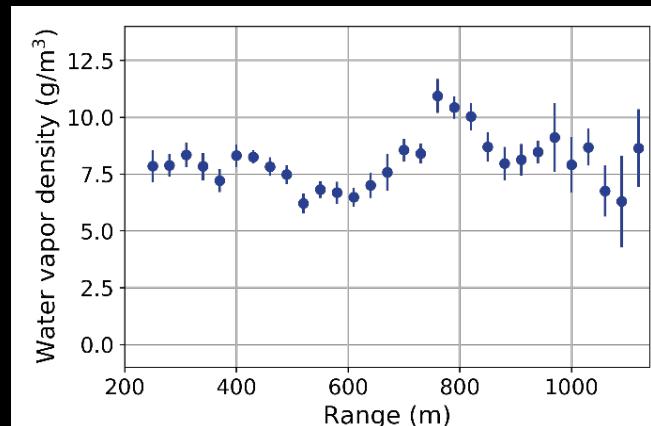
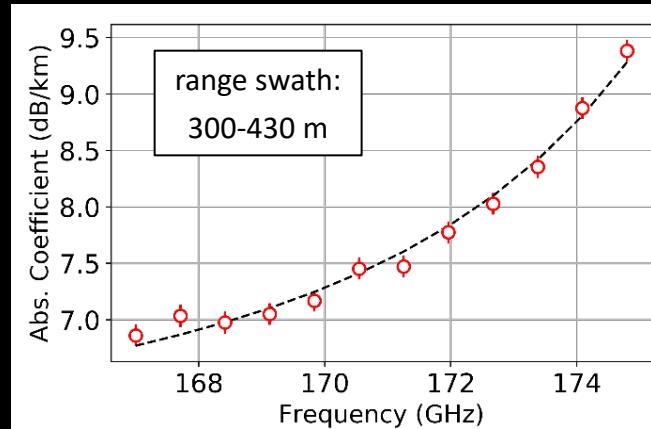
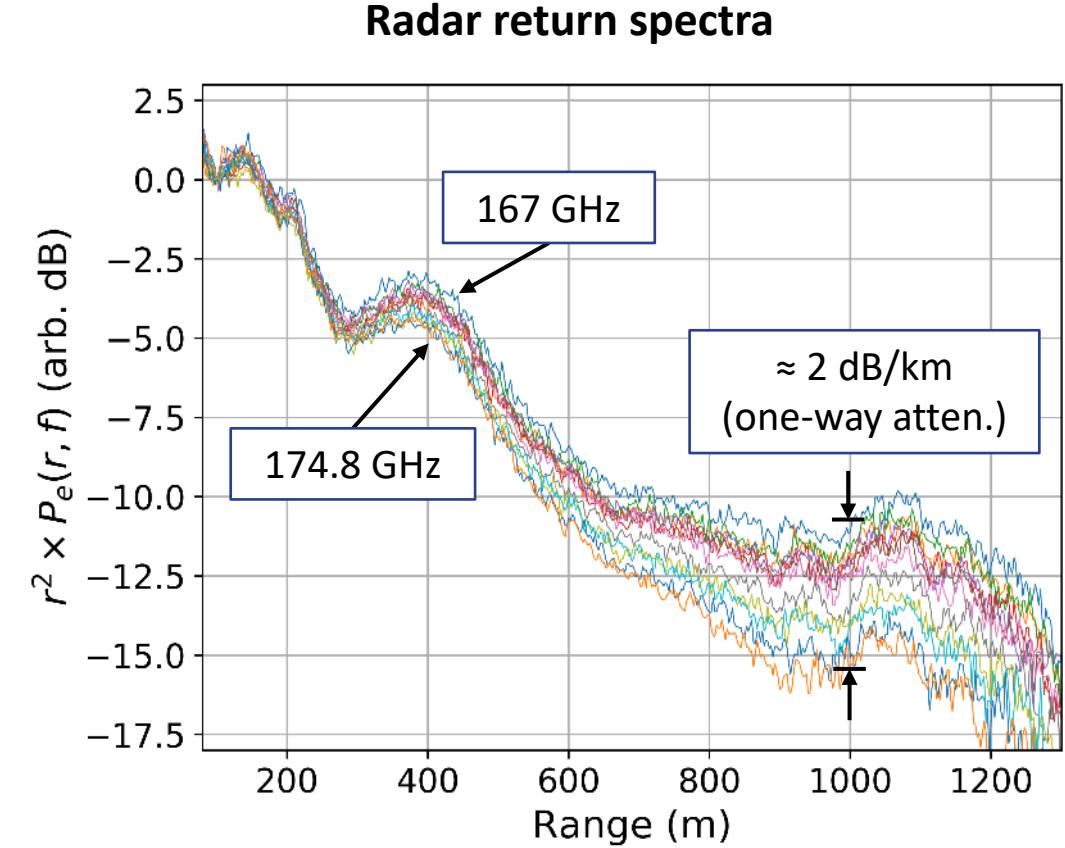
FMCW radar is appropriate for low-power source components
Challenging but possible to achieve necessary T/R isolation



Vapor In-cloud Profiling Radar (ViPR)

Pre-Decisinal Information -- For Planning and Discussion Purposes Only

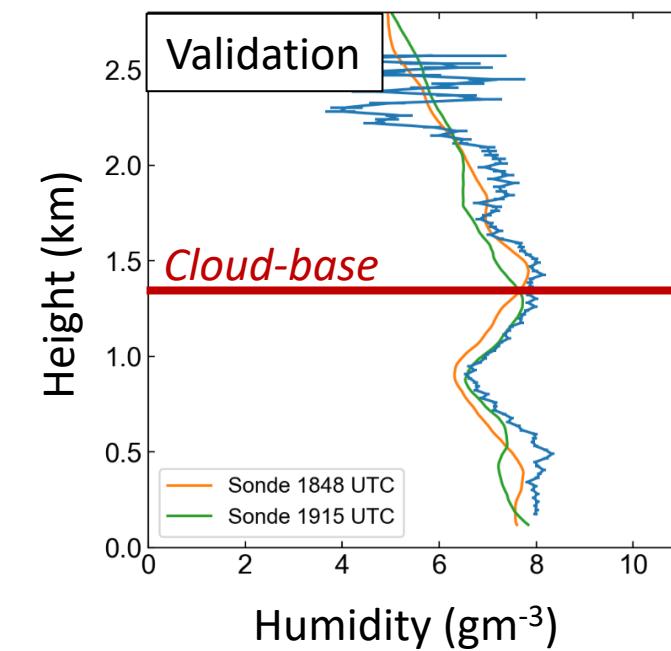
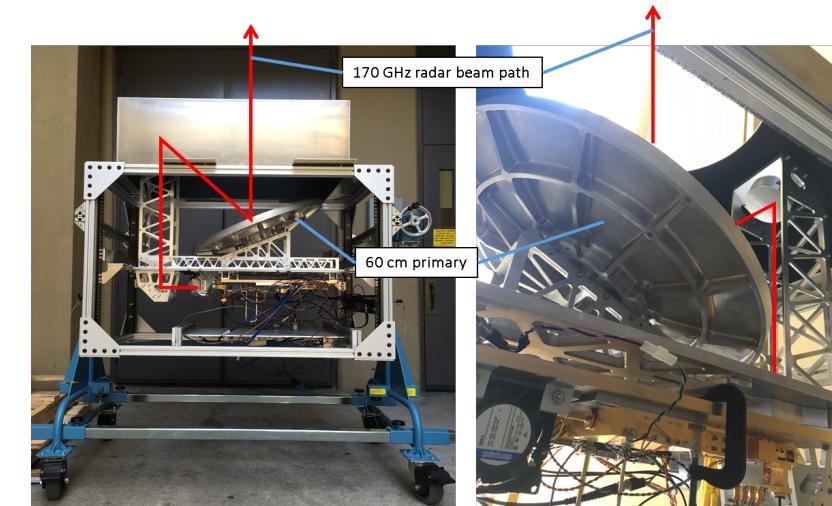
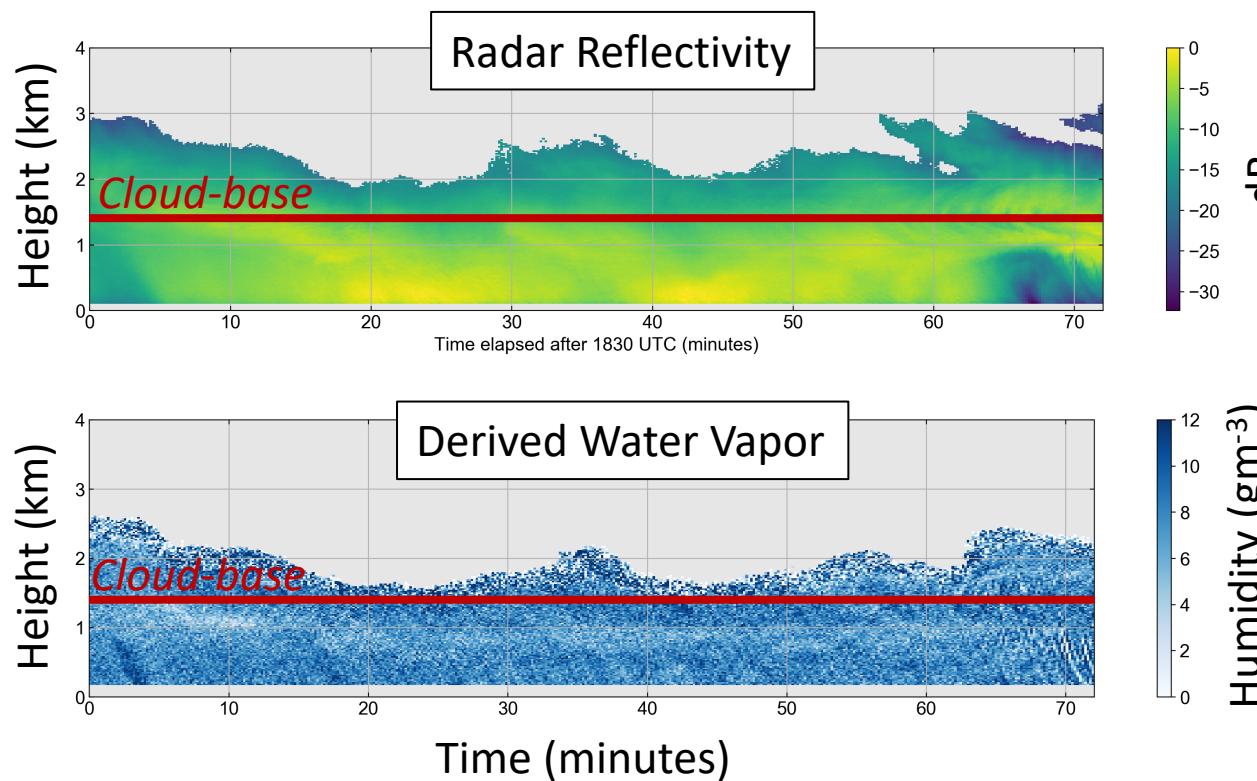
Precipitating Cloud Measurements





Vapor In-Cloud Profiling Radar (VI-PR)

- ESTO funded (IIP-16) G-band (~ 170 GHz) differential absorption radar
- First-ever** approach to remotely sense water-vapor in-cloud/precipitation
- Validation below shows RMSE < 10% @200 m vertical resolution
- Frequencies tuned to planetary boundary layer but can be extended to upper atmosphere



Jason-3

You can now follow RainCube on NASA's Eyes

<https://go.nasa.gov/2PGdBus>

QuikSCAT

RainCube

SMAP

